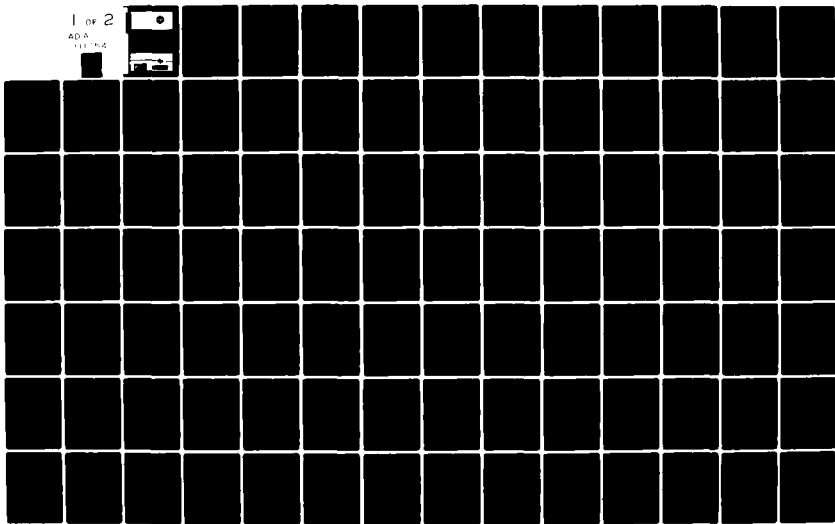
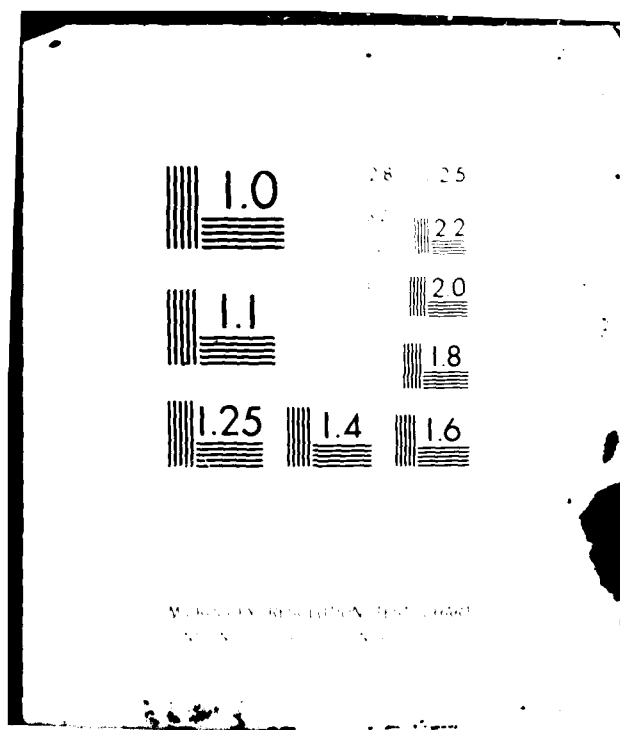


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THE PENNSYLVANIA STATE UNIVERSITY

**ANALYSIS OF WATERWAY SYSTEMS
SUMMARY REPORT**

By

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FINAL REPORT

CONTRACT NO. DACW23-72-C-0009

SEPTEMBER 1972

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In seeking to improve analytical tools for planning and evaluation of waterway transport systems, the results of a series of six reports on waterways systems simulation were analyzed. Study elements include: experimentation, utilization of system capacity, single lock studies, the statistical barge tow speed function, and the methodological design for water systems planning. A good bibliography is attached.		

ANALYSIS OF WATERWAY SYSTEMS

SUMMARY REPORT

by

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Final Report

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U.S. Army Corps of Engineers

North Central Division

Pennsylvania Transportation and Traffic Safety Center

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University Park, Pennsylvania 16802

September 1972

ABSTRACT

The results of a series of studies relating to simulation and analysis of inland waterway transportation systems are presented. Problems in waterway simulation experimentation, including determining the length of the transient period, identifying locks with Poisson arrival processes, and statistical analysis of autocorrelated data, are investigated. A system simulation model is used to study the operational effects of alternative means for increasing the utilization of existing capacity. A single lock simulator is applied to determine the effects of different lock processing rules, pleasure craft, and chamber separation on tow delays at various traffic levels. Several empirical equations for predicting the equilibrium speed of a tow in a river channel are derived by multiple linear regression analysis. Finally, the components and interrelationships of a comprehensive waterway systems planning methodology are described, with emphasis upon techniques for predicting waterway transportation demand.



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FOREWORD

In 1971, the Pennsylvania Transportation and Traffic Safety Center (PTTSC) completed a research program for the U.S. Army Corps of Engineers, devoted to the development and application of a set of computer models for the simulation of waterway transportation systems. The present report describes, in a summary fashion, research which represents an extension of the earlier work. Additional details concerning this research are provided in a series of technical memoranda, issued under the general title "Analysis of Waterway Systems," a list of which appears in the Appendix

It is assumed throughout this report that the reader is somewhat familiar with the inland waterway simulation models developed at PTTSC, although such familiarity is not essential for an understanding of the material presented herein. Appropriate references to previous PTTSC reports are provided as an aid for those who may not be so informed.

This work was performed for the U.S. Army Corps of Engineers, North Central Division, under contract number DACW23-72-C-0009. The contract period was from 15 September 1971 to 30 June 1972. The opinions, findings, and conclusions expressed in this publication, however, are those of the authors, and not necessarily those of the Corps of Engineers nor The Pennsylvania State University.

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The authors would like to take this opportunity to thank each member of the project team listed in the Foreword for their efforts in bringing this study to a successful conclusion. Although the study was truly a group effort, attributions for various phases of the work can be assigned roughly as follows:

- Chapter I - Bronzini, Hayward
- II - Rao, Desai, Keffalas, Nowading
- III - Rao, Bronzini, Carroll
- IV - Hayward, Carroll
- V - Hummel, Bronzini, Carroll
- VI - McLauchlan, Bronzini, Staadeker

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I. INTRODUCTION AND SUMMARY

Assessing the economic efficiency of improvements to the nation's waterway transportation system is a complex and difficult task. Furthermore, as demands upon the federal budget continue to escalate, it becomes increasingly important to scrutinize carefully and thoroughly all proposed investments in waterway transportation, both to avoid those projects with slim or illusory returns and to insure that truly efficacious projects are properly planned, designed, and operated.

In response to these needs, the Pennsylvania Transportation and Traffic Safety Center (PTTSC) of The Pennsylvania State University, under commission from the U.S. Army Corps of Engineers (COE), is engaged in a program of research with the objective of developing improved analytical tools for the planning and evaluation of waterway transport systems. The initial portion of this research was completed in July of 1971 and had as its immediate goal the development and application of computer simulation models suitable for exploring the operating characteristics of alternative navigation systems. The results of this research were documented in a six-volume technical report, supplemented by five technical memoranda, issued under the general title "Waterway Systems Simulation" in August of 1971.¹

During the past year, the simulation models developed at PTTSC have been turned over to the Corps of Engineers, which is now responsible for their operation and maintenance. Corps personnel at the Waterways Experiment Station in Vicksburg, Mississippi, have installed the models on COE

¹A complete list of PTTSC publications on waterway transport systems is provided in the Appendix.

computer facilities, where they are available for use by other Corps offices.

In conjunction with this transfer of operational responsibility for the models, Penn State's research activities have turned away from model development toward other topics. In particular, studies have been completed in the following general areas:

- (1) analytical techniques for waterway systems planning;
- (2) use of the simulation models to investigate alternative waterway operating policies;
- (3) refinement and further testing of selected model components; and
- (4) resolution of various practical and analytical problems relating to waterway simulation experimentation.

The next five chapters of this report present in-depth summaries of the individual (and, for the most part, independent) projects included in this research program. More detailed information regarding these studies is provided in a series of technical memoranda which supplement this report. The remainder of this chapter constitutes an executive summary of the entire study.

Methodological Design for Waterway Systems Planning

The methodological design segment of the past year's program relates to the first area listed above--development of analytical techniques for waterway systems planning. The primary emphasis of the study was upon demand forecasting and modal split techniques, and accordingly this summary will be confined to these topics.

1. Forecasting Commodity Flows

Simply stated, the job of a commodity flow forecasting model is to determine the origin-destination (O-D) movements of all commodities which are now or might potentially be shipped on the waterways for various periods of time in the future. Techniques for accomplishing this task can be segregated into two basic groups: structural and nonstructural methods.

Structural forecasts are conveniently thought of as economic or statistical models designed to explain observed commodity flows. Applicable techniques include single-equation regression models, econometric models or multiple-equation regression models, and input-output models. These methods all require a considerable degree of economic expertise and rather large quantities of data and, in addition, are beset with numerous statistical estimation problems. Also, the future values of independent variables must be known or estimated in order to use such models for forecasting purposes. The chief advantage of structural models is their supposed ability to capture the essence of underlying economic relationships, thereby eliminating dependence upon inexplicable historical phenomena to derive forecasts.

Nonstructural forecasts rely heavily on statistical analysis of time series data, projecting the future as a mathematically smoothed version of the past. Various smoothing techniques can be selected so as to weight different segments of the past in the manner most suited to the particular forecasting job at hand. Shift-share analysis provides another means of looking at changes in a variable over time and can be quite useful for examining differential growth patterns.

Inasmuch as both structural and nonstructural forecasting methods are necessarily tied to past and present conditions and preconceptions, the

art of "technological forecasting" has recently come into vogue as a possible means of envisioning the implications of radically different techno-social futures. Although technological forecasting would not be a practical means of preparing detailed commodity flow forecasts, it does appear that techniques of this genre could be useful for revising or modifying forecasts produced by a structural or nonstructural model.

Considering the current situation regarding forecasting methods and the specific mission of the Corps of Engineers, it was concluded that the development of a national interregional commodity flow model should be the responsibility of a federal agency with multimodal data collection authority, rather than the Corps. In the interim, the Corps should apply some of the more refined nonstructural forecasting techniques to projections of future waterborne commerce.

2. Modal Split Techniques

Given forecasts of future commodity flows, the next requisite component of a waterway systems analysis methodology is a method for allocating these flows among the transport modes competing for traffic in the area served by a waterway system. A further basic requirement is that such a modal split model must be responsive to the level of service provided by each mode.

Although several working modal split models have been developed for passenger transportation studies, relatively little progress has been made in solving the parallel problem for freight. Two statistical techniques which have looked promising in preliminary, small-scale studies are multiple regression analysis and discriminant analysis. Each of these methods has advantages and disadvantages, but the superiority of one vis-a-vis the other has yet to be established, and both suffer from the same drawbacks as structural forecasting methods do.

A rather simplified approach to freight modal split which has not been promulgated in the literature is the use of diversion curves. This method could be applied successfully in conjunction with forecasts of waterborne commerce only, i.e., data regarding other modes would not be needed. A suitably formulated and estimated diversion curve would show how much of the potential waterborne commerce between two ports would actually move on the waterway at various levels of average tow delay. Since the latter quantity can be derived by simulation, an iterative modeling procedure can be instituted to predict equilibrium values of waterborne traffic and tow delay, given an initial forecast of potential traffic.

3. Conclusions

The following two overriding themes became evident during the review of commodity flow forecasting and modal split techniques summarized above: (1) there are formidable obstacles to the development of econometric or statistical waterborne transport demand models; but (2) a great deal can be done with relatively simple methods to improve existing demand forecasting techniques, so as to make the resulting predictions more objective and more sensitive to waterway service levels. In short, the tools necessary for the development of a first generation waterway systems planning model are readily available; and it appears that the time has come for the Corps to either devise and implement such a methodology or else to reject the idea of waterway systems analysis.

Regardless of the exact form of the flow forecasting and modal split portions of a comprehensive waterway planning procedure, simulation will still be an integral part of the methodology. This is so because the delay values predicted by simulation will be used both as indicators of

system performance and as independent variables in the modal split and/or demand models. Consequently, it is essential to have a good understanding of the capabilities and limitations of the existing waterway simulation models developed at PTTSC. In response to this need, several simulation experiments using these models were conducted. These experiments are also of interest for what they reveal concerning inland waterway operations.

Simulation Experiments: Utilization of System Capacity

The system capacity simulation investigated opportunities for increasing the efficiency of inland waterway operations through better utilization of existing system capacity. The effects of nonstructural modifications such as limitations on flotilla size and reductions in locking times on tow delays were explored by means of the inland waterway system simulator, using the Illinois-Mississippi 10-lock subsystem as a test case.²

1. Objectives

The specific objectives of this study were to:

- (1) demonstrate methods for using simulation to analyze nonstructural alternatives;
- (2) assess quantitatively the effects of nonstructural improvements on system operations;
- (3) demonstrate procedures for statistical analyses utilizing simulation results; and
- (4) investigate the sensitivity characteristics of the simulation output.

²Document references will be provided in later chapters.

2. Study Procedures

The majority of the system simulations were for conditions in 1968, a base year for which ample data were available. An initial set of runs established confidence intervals for average delay per tow (ADPT) at each lock under existing conditions. Each alternative was then simulated by modifying the appropriate 1968 data values, and the new ADPT confidence intervals were computed. Comparison of confidence intervals (equivalent to the standard t-test) was then used to identify significant changes in ADPT. Analysis of variance was also applied to that subset of runs which constituted a factorial experiment.

The factors varied in this experiment were the following:

- (1) Flotilla size - limited to single lockage in 400-foot-by-110-foot chambers;
- (2) Dedicated equipment - 0%;
- (3) Locking times - 5% to 25% reductions in mean and/or standard deviation of each time component;
- (4) Chamber selection - no penalties allowed;
- (5) Traffic load - projected 1980 traffic.

Various factor combinations were also simulated.

3. Study Findings

The principal findings of this investigation were the following:

- (1) Flotilla size limitation produced 20% reductions in ADPT throughout the system and was particularly effective at higher traffic levels.
- (2) ADPT was judged to be relatively insensitive to the percentage of dedicated equipment in use.

- (3) Reductions in mean locking times resulted in more than proportional reductions in tow delays.
- (4) The combination of flotilla size limitation and 25% reduction in locking times produced reductions in ADPT on the order of 66% and enabled the system to accommodate approximately 300% of the 1968 traffic at comparable levels of delay.
- (5) The inland waterway simulation model was found to be a suitable tool for analyzing potential nonstructural improvements, since delays predicted by the model are sensitive to variations in the main controllable system elements.

Simulation Experiments: Single-Lock Studies

The single-lock study was devoted to simulating the operation of a single lock under various combinations of lock operating rules, commercial tow volumes, and pleasure craft volumes. The multiple-chamber single-lock simulator, LOKSIM, was used for this purpose.

1. Objectives

Four objectives were outlined for this study as follows:

- (1) to exercise the model in a variety of situations, in order to find and correct any remaining logic errors;
- (2) to test alternative locking rules under a range of tow volume loadings;
- (3) to examine the effects of pleasure craft on delays to tows; and
- (4) to evaluate the effect of chamber separation on tow delays.

2. Design of the Experiment

A dual chamber lock, consisting of a 1200-foot-by-110-foot chamber adjacent to a 600-foot-by-110-foot chamber, was simulated for this

investigation. Service times were based on data collected at Lock and Dam 27 on the Mississippi River. A constant mix of lockage types was input for all runs, and all double lockages (measured against a 600-foot chamber) were assigned to the large chamber.

The following factors were varied in this study:

- (1) Tow volume - 10.42, 19.20, 28.18, and 36.62 tows per day;
- (2) Locking rules - first in first out (FIFO), 3-up 3-down, serve opposing queues alternately (SOQA), and equalize queues;
- (3) Pleasure craft volume - 0, 28.8, and 50.0 per day;
- (4) Chamber Separation - adjacent, separated.

The null condition assumed was no pleasure craft, SOQA processing, and adjacent chambers. Three factorial experiments were then run, crossing tow volume with locking rules, pleasure craft volume, and chamber separation, respectively. The results were analyzed both graphically and by analysis of variance, with average delay per tow serving as the response variable.

3. Study Findings

The way in which tows are processed was found to significantly affect tow delays. At low tow volumes, these effects are less pronounced, but they become substantial at high volumes. Very little difference in tow delay was observed for the 3-up 3-down, SOQA, and equalize queues disciplines; but at arrival rates above 20 tows per day, the FIFO rule produced consistently higher delays.

Pleasure craft were also found to increase tow delays, particularly at high tow volumes. At lower volumes, however, many pleasure craft can be processed without seriously impeding commercial traffic.

Finally, chamber separation had no significant effect on average tow delay. Caution must be exercised in attempting to generalize this result, however, since special or unusual channel conditions could produce chamber entry times radically different from those used in this study. Hence, it will probably be necessary to simulate these special cases and draw localized conclusions.

In addition to gaining insight into the operational characteristics of the simulation models by using them to investigate problems of a practical nature, it is also necessary to monitor continuously the performance of the models' components, so as to insure that they will remain responsive to the needs of the waterway analyst. The next section summarizes a study conducted for this purpose.

A Statistical Barge Tow Speed Function

This part of the study deals with a particular component of the WATSIM model which is invoked to move tows through channels. The Howe Speed function, which currently performs this task, has an admittedly unknown capability for predicting the speeds of tows with high horsepower and is exceedingly complex and difficult to work with. As a first step toward removing these sources of concern, several alternative tow speed functions were developed by means of multiple linear regression analysis.

This investigation was made possible by the existence of a rather large data set containing simultaneous observations on the variables of interest. The Corps of Engineers had collected continuous locking operations data at all locks on the Ohio River and its tributaries during December of 1970 and January of 1971. For each lockage, the following values (among others) were recorded: vessel identification number; towboat

horsepower; day of the month; travel direction; time of arrival at the lock; departure time; number of loaded and empty barges; tow length, width, and draft; and lock name. Hence, it was a relatively simple matter to scan the data for two adjacent locks and identify individual tow trips for which the flotilla characteristics did not change. A set of 703 such observations were produced, supplemented by an additional 175 to serve as an independent data set.

Various transformations of the basic variables were taken to obtain additional independent variables for regression purposes. These included sums and differences, cross products, and logarithms. Potential speed equations were selected by means of a stepwise regression procedure. Both linear and log-linear functional forms were experimented with. For log-linear forms, including the Howe function, linear bias correction equations were estimated by simple linear regression, primarily to establish a consistent basis of comparison.

Seven acceptable functions were found, with fractions of explained variance (R^2) ranging from 0.74 to 0.83. The simplest equation was a linear form with five independent variables--direction of travel, towboat horsepower, number of loaded barges, number of empty barges, and average current speed--for which $R^2 = 0.75$. This equation had the further advantages that all coefficients had the expected sign and that some theoretical considerations dictated the particular forms in which the variables were introduced into the analysis.

All seven equations had considerably greater predictive power than the Howe function. This is particularly significant in view of the fact that the results obtained with the latter were virtually identical to those reported by Howe. Hence, it was concluded that a regression

equation should be substituted for the Howe function in WATSIM. Since the data did not contain observations on tows moving in restricted channels, however, additional work will be needed to produce an equation which is as sensitive to channel variables as is the Howe function.

Keeping the simulation models up to date, by means such as developing a new tow speed function, and ascertaining the operating characteristics of the models are not the only measures required to insure that the simulation segment of a waterway planning methodology is maintained in good working order. It is also necessary to devote some attention to the important subjects of experimental design and analysis. Some studies conducted as a part of the past year's research program relating to these topics are summarized in the next section.

Waterway Simulation Experimentation

Several problems of an experimental nature arise in performing simulation studies of waterway systems, including the following:

- (1) specifying the length of time required to reach steady state in the simulation model;
- (2) identifying locations where large systems can be separated into independent subsystems;
- (3) analyzing by correct statistical methods simulation-generated time series.

Some research findings pertaining to these problems are summarized below.

1. Length of the Transient Period

The Penn State Waterway Simulation models require the analyst to specify the length of time at the beginning of a run which is needed for the simulated system to proceed from an empty state to a state

characterized by "normal" traffic levels. System performance measures are then compiled only after this transient or "warm-up" period. But how long should this warm-up period be in order to guarantee that only steady state operation will be reflected in the output statistics?

This question was investigated by examining plots of average queue length versus simulation time for several inland waterway system simulations conducted with Penn State's WATSIM model. The approximate beginning point of a recurrent pattern in such a plot marks the end of the transient state. The study included lock utilization percentages of up to 80% and considered both locks close to important traffic generators and up to four locks in series (i.e., with no intervening major ports).

The study results for locks near major ports indicate that the length of the transient period is an increasing non-linear function of lock utilization, rising sharply at utilizations above 70%. For series locks, no such distinguishable pattern was observed. In all cases where utilization was less than 70%, the time to reach steady state was less than 4000 minutes. Hence, it was concluded that, for lock utilizations of less than 70% and for up to four locks in series, a WATSIM simulation run will require at most 4000 (simulated) minutes of warm-up time.

2. Lock Independence

If tows arrive randomly at a lock in a large system, then it is legitimate to split the system into two subsystems at some point between this lock and the preceding lock, thus allowing each subsystem to be simulated separately. The focus of this part of the study was upon methods for identifying such potential subsystem boundaries without resorting to extensive field investigations or pilot simulations. To this end, tow arrivals at locks on the Illinois, Mississippi, and Ohio rivers, as predicted with

the WATSIM model, were statistically tested for randomness. An attempt was then made to find a linear discriminant function for classifying locks as independent or dependent, using distance from and utilization of the preceding lock as independent variables.

The randomness tests revealed that only 13 arrival processes, out of the 80 considered, could be considered nonrandom at 5% significance. In the subsequent stepwise discriminant analysis, only distance was found to be significant, and then only at the 10% level. The corresponding discriminant function predicts random arrivals for locks more than 22.5 miles from the preceding lock, but produces an unacceptably large number of classification errors. Given the rather poor predictive power of the discriminant function, coupled with the high percentage of random arrival processes, it was concluded that reasonable care and judgment on the part of the analyst will usually be sufficient to avoid serious errors in delineating system boundaries.

3. Statistical Analysis of Simulation Time Series

Proper application of many statistical methods requires that the data used in the analysis be independent. Observations on a random variable generated at successive points in time in a simulation experiment, however, are generally autocorrelated; and treating them as independent underestimates the variance of the corresponding sample mean. This problem was avoided in previous waterway simulation work at PTTSC by taking observations at widely spaced intervals, at the expense of a considerable loss of statistical power.

In this study, a method for analyzing autocorrelated data suggested by Fishman was applied to a waterway lock simulation. Fishman's method essentially replaces the actual number of observations by an estimate of

the equivalent number of independent observations, obtained by considering the effects of autocorrelation. The results showed that, for 50 observations on average tow delay (one every 500 minutes for 25,000 minutes), the number of equivalent independent observations ranged from 50 to 36 as lock utilization increased from 27% to 90%. Hence, application of this method allows a rather large decrease in the required length of the simulation run, while still providing a sufficient number of independent observations.

In summary, it can be seen that a great deal of effort has been expended upon refining and exercising the PTTSC-COE inland waterway simulation models, and upon developing a consistent and logical framework for conducting meaningful simulation experiments. The simulation models, then, have reached the stage where they can be used confidently for waterway planning. It appears that the time has come to devote as much or more energy to bringing the other components of a waterway systems planning methodology to an equivalent developmental level.

Concluding Observations

At this point, the usual procedure followed calls for reviewing the research results and drawing up a long list of fruitful topics suitable for further study. In the present case any informed reader could perform this exercise equally as well as the authors, so no such list is forthcoming. The absence of this list, however, should not delude the reader into concluding that all the problems of waterway transportation systems analysis have been solved, for this is certainly not true.

What has been accomplished is that an excellent start has been made toward meeting the general objective set forth at the beginning of this research program--that of developing improved analytical methods for the planning and evaluation of waterway transport systems. Simulation models,

for both waterway systems and isolated locks, have been programmed and refined to the point where they can be used as working tools for planning and design studies. Various practical and theoretical problems attendant to the use of these models have been overcome, and the applicability of the models for analyzing a variety of alternative structural and nonstructural waterway improvements has been amply demonstrated. In addition, the results of the specific simulation studies completed to date, seminal though they are, provide some valuable insights into what future waterway development programs appear to be the most attractive. Finally, the basic elements and modular interrelationships of a comprehensive waterway systems planning methodology have been formulated, and some guidelines for how to proceed with the construction of a first generation model system have been suggested.

The job remaining is a large and complex one, but it is also a feasible undertaking and is worthy of the best efforts which can be brought to bear on it. In this time of controversy surrounding proposed revisions in federal criteria for water resource investments and the possible environmental impacts of navigation projects, it is absolutely essential that the direct economic consequences of waterway capacity additions be firmly established. The analytical techniques made available through this research, plus those which have been suggested for development in the immediate future, constitute a viable repertoire of methods for estimating these consequences as closely as is possible, given the present state of man's knowledge and abilities. The guardians of the federal budget and the protectors of the environment can hardly ask for more, but neither should they require less.

II. WATERWAY SIMULATION EXPERIMENTATION

Successful use of the waterway system simulation models developed at Penn State [1]¹ for studying the performance of waterway systems is contingent upon the solution of several problems relating to simulation experimentation techniques. These include the following:

- (1) determination of the length of the transient period for waterway system simulations;
- (2) identification of locations where large systems can be split into time-independent subsystems;
- (3) development of statistically powerful techniques for analyzing simulation-generated time series.

Research results pertaining to the solution of these problems are presented in this chapter.

Length of the Transient Period

1. Nature of the Problem

The term "steady state," when applied to any system, simply means that over a long time span the operational characteristics of the system are not time varying. This is contrasted with the "transient state," which is defined as a condition in which performance measurements are changing with time in a regular fashion.

The Penn State simulation models operate in both of the above modes. A simulation run is started with the system in the idle state, in which no service is being performed and no entities are awaiting service. Early

¹Numerals in brackets refer to correspondingly numbered items in the list of references at the end of the report.

arrivals, then, have a higher than usual probability of obtaining service quickly, so the mean of a sample which includes the early arrivals will be biased. This so-called warm-up period is a transient state. Once queues at service facilities are stabilized, the system is in steady state.

The amount of time required for a system to reach steady state is of critical importance to the analyst, as he will normally want to make decisions based only on steady state performance measures. Identification of steady state conditions, however, is complicated by the fact that random fluctuation is an inherent characteristic of queuing data, and hence the steady state is not synonymous with a constant state.

In the Penn State simulators, the steady state problem is disposed of by the commonly employed strategy of having the analyst specify as an input item the initial time period which is to be treated as the transient state. The purpose of this investigation into the length of the transient period was to determine how long this warm-up should be for various traffic levels and system geometries.

2. Methodology

Various methods for identifying the end of the transient period have been discussed by Bhat and Mann [2], and Gordon [3]. This study made use of a simple graphical technique proposed by Schroer [4], which consists of examining plots of average queue length versus simulation time. If there is a recurrent pattern in such a plot, the approximate beginning point of this pattern marks the start of what can be considered to be the steady state. In the absence of such a pattern, on the other hand, smoothed values of average queue length will usually be monotonically increasing with time, which indicates that steady state has not been reached.

This method was applied to six inland waterway simulation runs made with the WATSIM model [5]. Four of the runs were for a hypothetical system, consisting of four dual chamber locks with a constant interlock distance of 50 miles and two external end ports. The traffic mix featured equal numbers of single and double lockages, and the utilization rates were 27.6%, 67%, 75%, and 80%. The remaining two runs were for the Illinois-Mississippi [6] and Ohio River [7] systems, utilizing data representative of conditions in 1968.

3. Results and Conclusions

Typical graphical results are shown in Figures 2-1 and 2-2, which are plots of average queue length for each 500-minute interval of simulation time (i.e., if X is an abscissa value, then simulation time = $500X$). In the first case, a stable pattern emerges after six observations, while no such stability occurs for the second. Complete results are reported elsewhere by Desai [8].

A summary of the study findings is given in Figure 2-3, in which the length of the transient period is plotted against lock utilization percentage. The only discernible trend appearing is in those values for single locks, i.e., those with major ports on either side. Here, time to reach steady state appears to be an increasing nonlinear (possibly quadratic) function of lock utilization and would appear to rise drastically at utilizations above 70%.² For series locks, those without intervening ports, there is no distinguishable pattern. In all cases, however, the time to reach steady state is less than or equal to 4000 minutes.

²This is very similar to the normal behavior of delay vs. utilization in queuing systems.

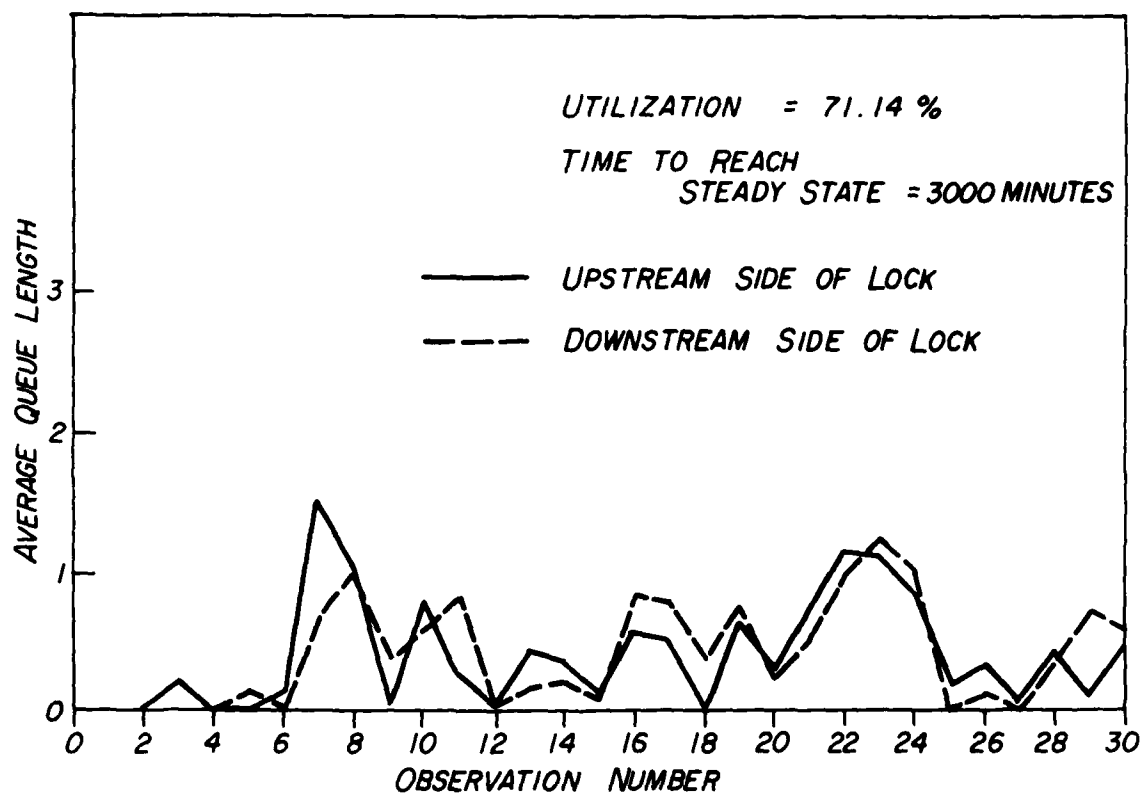


Figure 2-1 Queuing Behavior at L&D 2 of the Hypothetical System

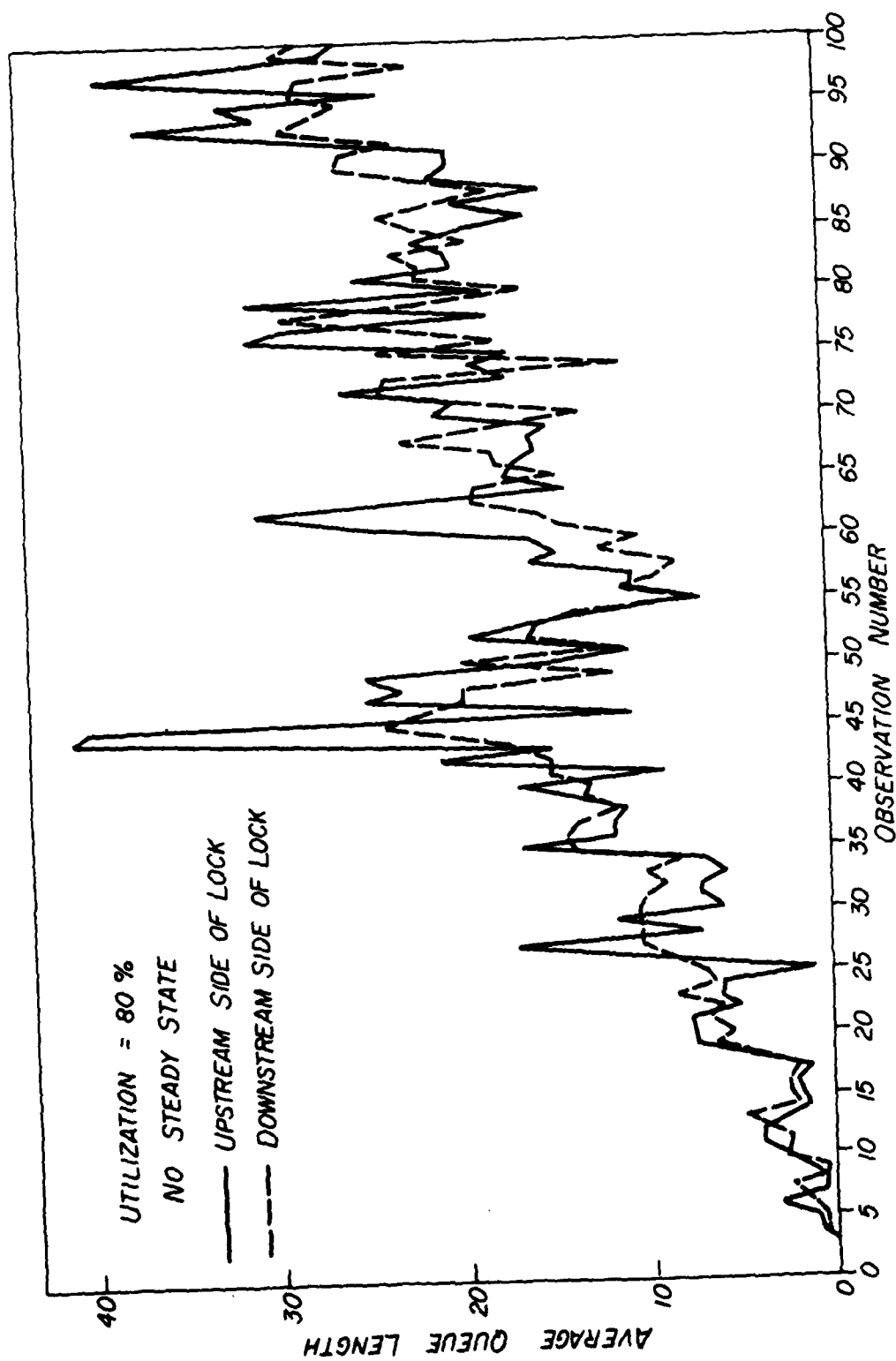


Figure 2-2 Queuing Behavior at L&D 1 of the Hypothetical System

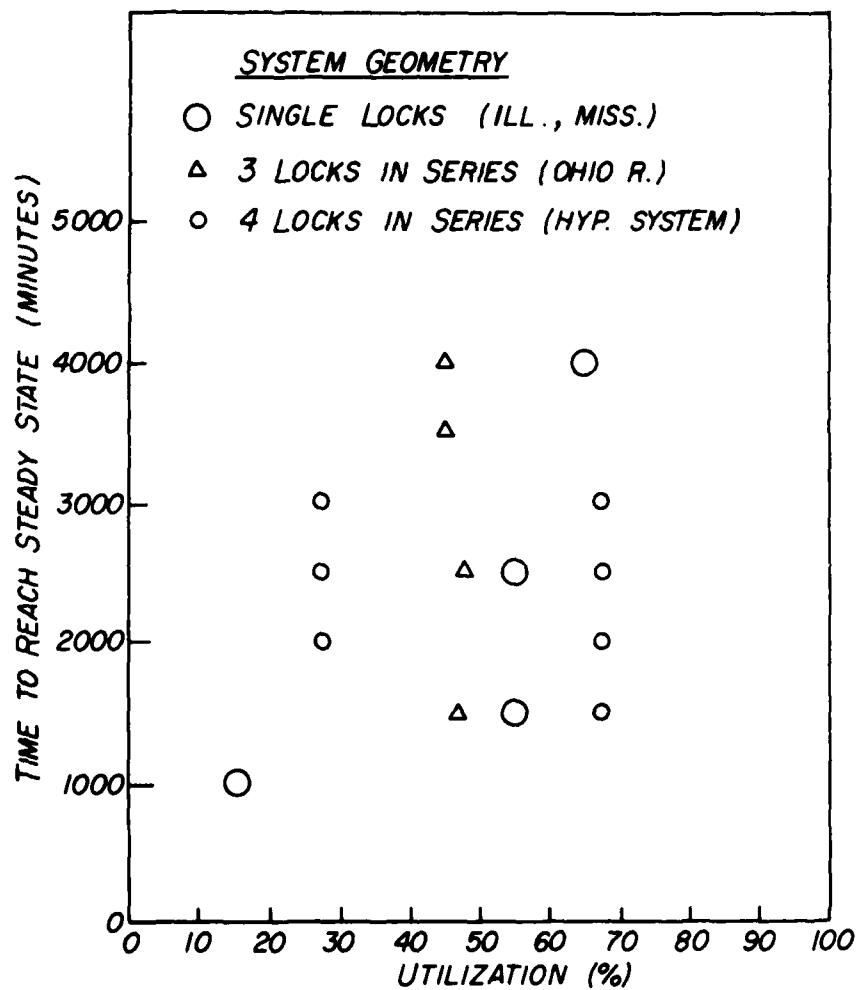


Figure 2-3 Length of Transient Period vs. Lock Utilization

In view of the above results, it is concluded that, for lock utilizations of less than 70% and for systems with up to four locks in series, the waterway system will reach steady state after approximately 4000 minutes of simulation time. If a system contains more than four consecutive locks, a longer warm-up period will be needed, the length of which can be determined via the type of analysis demonstrated above.

Lock Independence

One of the reasons for simulating inland waterway systems, rather than confining attention to individual locks, is the possibility that the distribution of tow arrivals at one lock may be influenced by the service processes at the immediately preceding lock. If the tow arrivals at a lock follow a Poisson distribution, however, then the queuing processes at this lock are stochastically independent of what has occurred at the preceding lock.³ The practical importance of this observation is that a large system could be split into two smaller subsystems between two such independent locks, and each subsystem simulated separately. Methods for identifying such potential division points were explored by studying tow arrival processes at locks on the Illinois-Mississippi [6] and Ohio River [7] waterway systems.

1. Identification of Independent Locks

A necessary and sufficient condition for the existence of a Poisson arrival process is that the distribution of the time gaps between successive tow arrivals be negative exponential.⁴ Hence the first step of the

³This is a well known result from the theory of stochastic processes. See for example, Feller [9], pp. 444-451.

⁴This elementary queuing theory result is proved in [10], p. 295.

study was to test the goodness-of-fit of the tow interarrival distributions at all locks (as predicted in simulation runs for the year 1968) to a negative exponential distribution, using a Chi-Square test. All locks for which the null hypothesis was rejected were subsequently considered to have non-Poisson inputs, and hence to be dependent.

Complete data and results are reported elsewhere by Desai [11]. For the Illinois-Mississippi simulation, 5 locks out of 10 had non-Poisson arrivals at 5% significance, and all locks had Poisson inputs at the 1% level. Of the 30 locks on the Ohio River, 8 had non-random arrivals at 5% significance, while 5 were in the dependent category if the significance level is reduced to 1%.

The classification scheme demonstrated above is completely general and could be used to identify system division points, given sufficient observations on tow arrivals. Since this test is not very powerful, a large number of observations would be needed. Hence, it would be desirable to have available a simple quantitative procedure for classifying locks as independent or dependent on the basis of some readily measurable system variables. The multivariate statistical technique of linear discriminant analysis is ideally suited for exclusive categorization problems of this sort and is applied below.

2. Discriminant Analysis

The objective of discriminant analysis is to classify observations, according to the values of a set of independent variables, into one of two or more mutually exclusive and exhaustive categories. For most practical applications, a linear discriminant function of the independent variables is formulated and its parameters estimated so as to minimize classification errors [12].

For the present study, it was desired to classify locks into the categories of independent and dependent (i.e., Poisson and non-Poisson arrivals, respectively). The results of the Chi-Square analysis were used to derive 11 observations in each category. For this exploratory study, only two independent variables were used. These were: (1) utilization of the preceding lock and (2) distance from the preceding lock. As the former increases and the latter decreases, tow arrivals should become more regulated; and hence, the subject lock should tend toward dependence. The data for this study are displayed in Table 2.1.

A stepwise discriminant analysis was performed on the data, using the BMD07M program of the UCLA biomedical statistical package [13]. Only the distance variable was selected as significant, and the discriminant functions were as follows:

$$\text{Independent Locks: } Z_1 = -4.17147 + 0.26571D \quad 2-1$$

$$\text{Dependent Locks: } Z_2 = -2.46066 + 0.18941D \quad 2-2$$

where D is the distance between locks, in miles.

The corresponding F statistic, with 1 and 20 degrees of freedom, was 3.15, which is significant at $\alpha = 0.10$.

To apply these results, one simply substitutes the value of D into 2-1 and 2-2, and that function which produces the largest Z value indicates the proper classification.⁵ That is, if $Z_1 > Z_2$, the lock should be assigned to group 1. A simpler procedure can be derived for the one-variable case by equating Z_1 and Z_2 and solving for D, which results in $D^* = 22.42$ miles. Hence, locks which are more than 22.42

⁵Equivalently, one could look at $Z = Z_1 - Z_2 = -1.71081 + 0.07630D$, and classify an observation into group 1 and 2 according to whether Z is greater or less than zero, respectively.

TABLE 2.1. OBSERVATIONS FOR DISCRIMINANT ANALYSIS

<u>Lock & Direction</u>	<u>Utilization of Adjacent Lock (P), %</u>	<u>Distance from Adjacent Lock (D), miles</u>	<u>Group*</u>
<u>Ohio River</u>			
L&D 15 down	54.64	16	1
up	51.76	17	1
L&D 16 up	54.05	21	1
L&D 44 up	78.56	39	1
L&D 45 down	79.21	39	1
up	47.32	18	1
L&D 46 down	47.37	35	1
up	67.56	20	1
L&D 47 down	67.73	20	1
L&D 48 up	70.75	35	1
L&D 49 down	66.15	35	1
Pike Island up	52.03	3	2
L&D 13 down	52.03	9	2
L&D 44 down	78.30	30	2
L&D 47 up	66.15	32	2
L&D 48 down	67.56	32	2
L&D 50 down	70.75	32	2
<u>Illinois River</u>			
Marseilles up	53.92	13.6	2
Starved Rk. down	55.34	13.6	2
L&D 25 up	100.00	16.1	2
L&D 26 down	35.93	16.1	2
L&D 27 down	100.00	7.9	2

*Group 1 = Independent locks, Group 2 = Dependent locks

miles from the preceding lock would be classified as independent according to the above results. The probability that the observation belongs to the selected group is then computed as

$$P_k = \frac{1}{\sum_{i=1}^g e^{(Z_i - Z_k)}} \quad 2-3$$

where k is the selected group, and g is the number of groups. Hence, as the discriminant functions approach a common value, P approaches 1/g (= 0.5 in this case).

The results of applying the discriminant function to the data in Table 2.1 are given in Table 2.2. Of the 22 observations, only 12 were classified correctly. If the observations were to be classified randomly, the total number of correct classifications would be a binominal random variable with parameters $n = 22$, $p = 0.50$, and a score of 12 right or better would occur about 29.7% of the time. This is a relatively poor degree of predictive ability and is somewhat lower than the F statistic quoted above might lead one to expect.

Reviewing Table 2.1, it is seen that six of the independent locks have D values between 16 and 21 miles, which is very close to the

TABLE 2.2. DISCRIMINANT ANALYSIS RESULTS

Actual Class	Discriminant Function		Total
	Independent	Dependent	
Independent	5	6	11
Dependent	4	7	11
Total	9	13	22

discriminant value, D^* . If D^* were reduced to 16.9 miles, the number of correct classifications would increase to 17. However, the statistical properties of the corresponding discriminant function would be altered. Obviously, one could also raise D^* to 32.1 miles, thereby increasing the number correct to 16 (i.e., all of group 2, plus 5 observations in group 1).

The relevant point is that the parameter estimates of 2-1 and 2-2 are based on a normality assumption and do not give more weight to one group over another. Different assumptions would produce different discriminant functions. In the present application the discriminant function can only be used as one guideline for selecting a system boundary point.

3. Conclusions

A more accurate and generally applicable discriminant function for identifying independent locks could probably be found if additional independent variables were included in the analysis. The lock utilization variable proved to be unsuitable for this purpose, primarily because the existence of ports between the locks weakens the influence of this variable. That is, if the departure of tows from a port is a Poisson process (which is a reasonable assumption), then tow arrivals at the nearest lock will also tend to be Poisson, regardless of the value of the distance variable. Desai [11] suggests that weighting the utilization of the preceding lock by the relative proportion of nonstop tows and tows arriving from an intermediate port might provide a good independent variable.

Perhaps the most significant result of this study is that, of the 80 lock arrival processes considered, only about one-eighth could reasonably be classified as non-Poisson. Hence, the assumption of Poisson arrivals at any given lock would appear to have a high probability of being

correct, and reasonable care and judgment on the part of the analyst will usually be sufficient to avoid serious errors in delineating system boundaries. Further, if setting the system boundary correctly appears to be critical to the success of a particular simulation study, analysis of lock records or other data on tow arrivals, using the Chi-Square test procedure, will settle the issue.

Statistical Analysis of Simulation Time Series

1. Introduction

Proper application of many statistical methods requires that the data used in the analysis be independent. In most simulation-generated time series data, however, there is a certain degree of dependence on past events. That is, the value of some random variable at time t is usually dependent on its value at some time preceding t . One measure of this degree of dependence between observations in a simulation is called serial correlation. The corresponding parameter for the population is called autocorrelation.

Testing the difference of some mean response is the most commonly applied method for comparing the results of two simulation experiments. It will often be the case in these experiments, and in particular in queuing problems, that the stochastic processes of interest are non-normal. Under this circumstance the sample mean is not necessarily a normal variate. Diananda [14], however, has established that the sample mean of autocorrelated data can be shown to approximate a normal distribution as the sample size increases. Therefore, the method of estimating the mean value of the distribution by its arithmetic average remains satisfactory for autocorrelated data. However, the variance of autocorrelated data is

not related to the population variance by the simple expression σ^2/n , as occurs for independent data, but is biased by a term due to autocorrelation. This term is positive in situations that normally occur in a simulation experiment so that, if it is ignored, the variance is underestimated.

Fishman [15] has suggested a method for studying time series by exploiting autocorrelation rather than eliminating it. The approach centers on estimating the variance of the sample mean for the original data from "sufficiently long" sample records.

In this portion of the research, the method suggested by Fishman was applied to the stochastic processes on the inland waterways. A one-lock system was simulated at various levels of traffic to study the effect of lock utilization on autocorrelation.

2. Theoretical Background

The variance of the sample mean computed from independent data, as said before, is inversely proportional to the number of observations. This is not true for autocorrelated data. For sufficiently long sample records, however, it can be shown that the variance of the sample mean in autocorrelated data is inversely proportional to a fraction of the number of observations. This fraction of the number of observations may be regarded as the number of equivalent independent observations, \hat{N} .

To facilitate this calculation, Fishman has introduced the concept of the correlation time of a process. If a process is observed for a period equal to n correlation times, then one may be said to possess, from the point of view of the variance of the sample mean, $n/2$ independent observations [15].

Applying these concepts, Fishman calculates the estimated variance, \hat{V} , the correlation time, γ^* , and the equivalent independent observations, \hat{N} , as follows:

Define $\{X(T), -\infty \leq t \leq \infty\}$ as a covariance stationary⁶ stochastic process with observations of X_t taken at unit intervals.

By definition,

$$\mu = E(X_t) \quad 2-4$$

$$R_Y = E[(X_t - \mu)(X_{t-\gamma} - \mu)], \gamma = 0, 1, 2, \dots, \infty \quad 2-5$$

$$\hat{R}_Y = \frac{1}{T - \gamma} \sum_{t=1}^{T-\gamma} (X_t - \bar{X})(X_{t+\gamma} - \bar{X}) \quad 2-6$$

where μ is the population mean, \bar{X} is the estimated sample mean, T is the total number of observations, and R_Y is the autocovariance function. Then,

$$\hat{V} = \frac{1}{T} [\hat{R}_0 + 2 \sum_{\gamma=1}^M (1 - \gamma/M) \hat{R}_Y] \quad 2-7$$

where \hat{R}_0 is the sample variance, and M is the number of lags.⁷

$$\gamma^* = T \hat{V} / (2\hat{R}_0) \quad 2-8$$

$$\hat{N} = T / (2\gamma^*) = \hat{R}_0 / \hat{V} \quad 2-9$$

When the number of lags is inadequate for good resolution, estimates of V increase in magnitude as M increases, and stabilize in value when resolution is accomplished. If V is continued to be estimated for larger M , the estimates eventually decline due to the bias term introduced by

⁶This requires that the second moment, $E[X(t)X(t + \gamma)]$, be finite and be a function only of γ .

⁷ M determines the number of past observations that will contribute to the autocovariance function.

replacing the mean μ by the sample mean \bar{X} above. To avoid this bias, the number of lags M must be significantly smaller than the sample record length T ; and yet, good resolution requires that M be sufficiently large.

3. Application to Waterway Simulation

The technique outlined above was applied to the simulation of a one-lock system with Poisson arrivals and a multicomponent general service distribution. The multiple channel deep draft GPSS simulator developed at Penn State [16] was used for this experiment, primarily because of its flexible microscopic output capability.

Simulation was run for 50,000 minutes with the first 5,000 minutes⁸ being used as warm-up to achieve steady-state conditions. Observations were taken every 500 minutes, and the number of lags M was given values between 2 and 10. The tows were externally supplied with Poisson arrivals at four rates, producing facility utilizations of 27%, 53%, 70%, and 90%. Estimations of the variance of sample mean were made for T values of 10,000, 20,000, 30,000, 40,000, and 50,000 minutes, so that appropriate values of T and M could be determined for the subsequent calculations of γ^* and \hat{N} .

The main response of interest was average delay per tow (ADPT), which was calculated for each 500-minute interval as follows: If TD_t is the cumulative total delay in minutes at time t and TT_t is the cumulative total number of tows at time t , then

$$ADPT_j = \frac{TD_t - TD_{(t-500)}}{TT_t - TT_{(t-500)}} \quad \begin{matrix} t = 5500, 6000, 6500, \dots, T \\ j = 1, 2, \dots, \frac{T - 5000}{500} \end{matrix} \quad 2-10$$

⁸See the first section of the chapter.

The estimated variance values for lock utilization of 90% are given in Table 2.3. Looking at the values of \bar{X} and \hat{R}_0 , it seems clear that T should be at least as large as 30,000 minutes (with 5,000 minutes of warm-up). It is further evident that resolution is accomplished at $M = 4$ which means the maximum lag in minutes is $4 \times 500 = 2000$. For values of $M < 4$, resolution is inadequate; and for values above 4, the bias term, due to estimation of the mean, becomes significant. Table 2.4 gives values for γ^* and \hat{N} at M values of 2, 4, and 6. The calculations for M equaling 4 give the most conservative \hat{N} values, indicating that when the number of lags M is either too small or too large, the degree of autocorrelation would be underestimated.

Table 2.5 presents \hat{N} for various traffic levels at appropriate values of M. Note that as facility utilization goes up, the degree of autocorrelation also increases and hence \hat{N} decreases. It is only this trend that is important, not the absolute values of \hat{N} presented in Table 2.5. The latter must be determined for each system being simulated, preferably through a pilot run in the manner suggested above. For large systems with more than one sequential service facility, both M and γ^* would be a function of the number of such facilities and the distance between them.

The equivalent independent observations, \hat{N} , could be used in standard statistical analysis as the requisite degrees of freedom. Jenkins [17] has further suggested that the distribution of \hat{V}/V may be approximated by that of a multiple of χ^2 with equivalent degrees of freedom

$$r = \frac{1.5 T}{M}$$

This allows the user to construct approximate confidence intervals for the variance (V) of the sample mean.

TABLE 2.3. ESTIMATED VARIANCE OF SAMPLE MEAN FOR LOCK UTILIZATION OF 90%

Simulation Time (T)	Number of Observations n	ADPT (\bar{X})	Sample Variance \hat{R}_0	Estimated Variance of Sample Mean (V) Where M equals			
				2	4	6	10
10000	10	31.0499	1598.348	110.817	171.617	254.617	-
20000	30	53.899	3783.792	158.294	186.744	139.244	119.844
30000	50	57.549	2879.115	76.052	80.485	60.718	45.818
40000	70	57.175	2605.273	50.291	48.591	32.616	28.566
50000	90	59.515	2965.344	39.024	39.973	19.791	22.296

TABLE 2.4. CORRELATION TIME AND EQUIVALENT INDEPENDENT OBSERVATIONS

FOR LOCK UTILIZATION OF 90%

Simulation Time (T)	Correlation Time (γ^*) ^a Where M equals			Equivalent Independent Observations (N) Where M equals		
	2	4	6	2	4	6
30000	0.792	0.838	0.632	38	36	47
40000	0.772	0.746	0.501	52	54	> 70 ^b
50000	0.651	0.667	0.330	76	76	> 90 ^c

^aThese numbers are fractions of the observation interval (500 minutes). Therefore, a value of 0.792 is equal to 396 minutes.

^{b, c} In these cases, the correlation time was biased enough that an erroneous conclusion is reached; namely, that all observations are independent.

TABLE 2.5. AUTOCORRELATION PARAMETERS FOR
VARIOUS UTILIZATION RATES

Simulation Time (T)	No. of Obs. (n)	Equivalent Independent Observations (\hat{N})			
		UR = 90%	UR = 70%	UR = 53%	UR = 27%
30,000	50	36	48	46	>50
40,000	70	54	63	67	>70
50,000	90	76	80	83	86

4. Relation to Steady State

In examining Table 2.3, the reader may have noted that there are still some transient effects in the response variable. Despite the fact that the initial 10 observations were discarded, \bar{X} does not stabilize appreciably until time 20,000. This suggests that a refined estimate of the length of the transient period could be obtained as follows: (1) calculate values of \bar{X} and \hat{R}_0 as in Table 2.3 on the basis of an initial assumption as to the length of the transient period; (2) select a new value for warm-up time by inspecting the time-varying behavior of these statistics, and repeat the analysis. In the case of the present example, it appears that a warm-up time of 10,000 minutes would be appropriate, which is reasonable in view of the high utilization rate. Selection of the proper warm-up time could reduce the required run length to $T = 20,000$ in this case, although the number of equivalent independent observations will also influence this choice.

5. Conclusion

The nature of simulated time series data invalidates analysis by methods applicable to independent observations. Further, Fishman and Kiviat [18] have suggested that the comparison of the autocorrelation structure of two processes through their spectra offers considerably more insight into the true nature of the processes than does a simple comparison of means. For those who desire the latter, however, the method suggested by Fishman [15] and further explored in this chapter appears to be a simple and feasible tool for treating autocorrelated data. The method also appears to be applicable in the use of other statistical techniques requiring the independence assumption.

Operational guidelines and example applications are presented elsewhere by Rao [19].

Discussion

The more pragmatic reader may be inclined to dismiss the issues explored in this chapter as statistical fine points with no practical importance. This is decidedly not the case. Proper application of the research findings presented above can significantly reduce the cost and improve the reliability and accuracy of a waterway simulation study. In this regard, the techniques presented are more important than the specific numerical results, although conservative values drawn from the latter could be used if the necessity arises.

Some of the results derived in this chapter were made use of for the simulation experiments described in the succeeding two chapters, where their practical significance will become more evident.

III. SIMULATION EXPERIMENTS: UTILIZATION OF SYSTEM CAPACITY

This chapter presents the results of an experimental investigation of opportunities for increasing the efficiency of inland waterway operations through better utilization of existing system capacity. The effects of such nonstructural modifications as limitations on flotilla size and improved operating procedures in lock areas were explored with the inland waterway systems simulation model developed at The Pennsylvania State University [1]. The Illinois-Mississippi 10-lock subsystem was used as a test case, and various perturbations in the simulation input data were introduced in a controlled fashion. All test results were examined for statistical significance.

Objectives of the Study

The simulation model used for this experiment had previously been applied to studies of alternative future structural configurations for a number of inland waterway systems [1, Chapter 6]. The utility of the model for analyzing prospective low cost, nonstructural means of increasing system capacity, however, had not been empirically demonstrated. Furthermore, the potential efficacy of such improvements in reducing tow delays, the subject of a recent study by the Corps [20], had not been quantified nor examined from a systems viewpoint. Finally, the statistical properties of the simulation output had never been fully exploited, and the sensitivity of the output to changes in the input data had not been adequately investigated.

In light of the situation described above, the specific objectives of this study were to:

- (1) demonstrate methods for using the inland waterway simulation model to analyze nonstructural alternatives;
- (2) assess quantitatively the effects of nonstructural improvements on system operations;
- (3) demonstrate procedures for statistical analyses utilizing simulation results; and
- (4) investigate the sensitivity characteristics of the simulation output.

Study Procedures

As mentioned previously, this study centered around simulation of the Illinois-Mississippi 10-lock subsystem. This system, which is shown in Figure 3-1, is comprised of the seven navigation locks on the Illinois Waterway and Locks 25, 26, and 27 on the Upper Mississippi River. This system was selected for study because the requisite input data were readily available, since the authors had previously simulated alternative structural improvements to it [6].

The first task performed was the establishment of confidence intervals for average tow delay at each lock in the system for the year 1968, which was the base year in the previous study. This was accomplished by making six simulation runs¹ of 48,200 minutes each (including a 5,000-minute warm-up period), and obtaining intermediate output at 18,000 and 36,000 minutes of simulation time, in addition to final output. The resulting 18 observations² on average tow delay were used to develop delay

¹Different strings of pseudorandom numbers were used for each run.

²This study was conducted before the analytical techniques reported in the last section of Chapter II had been fully explored. Hence, it was necessary to use extremely conservative sample sizes.

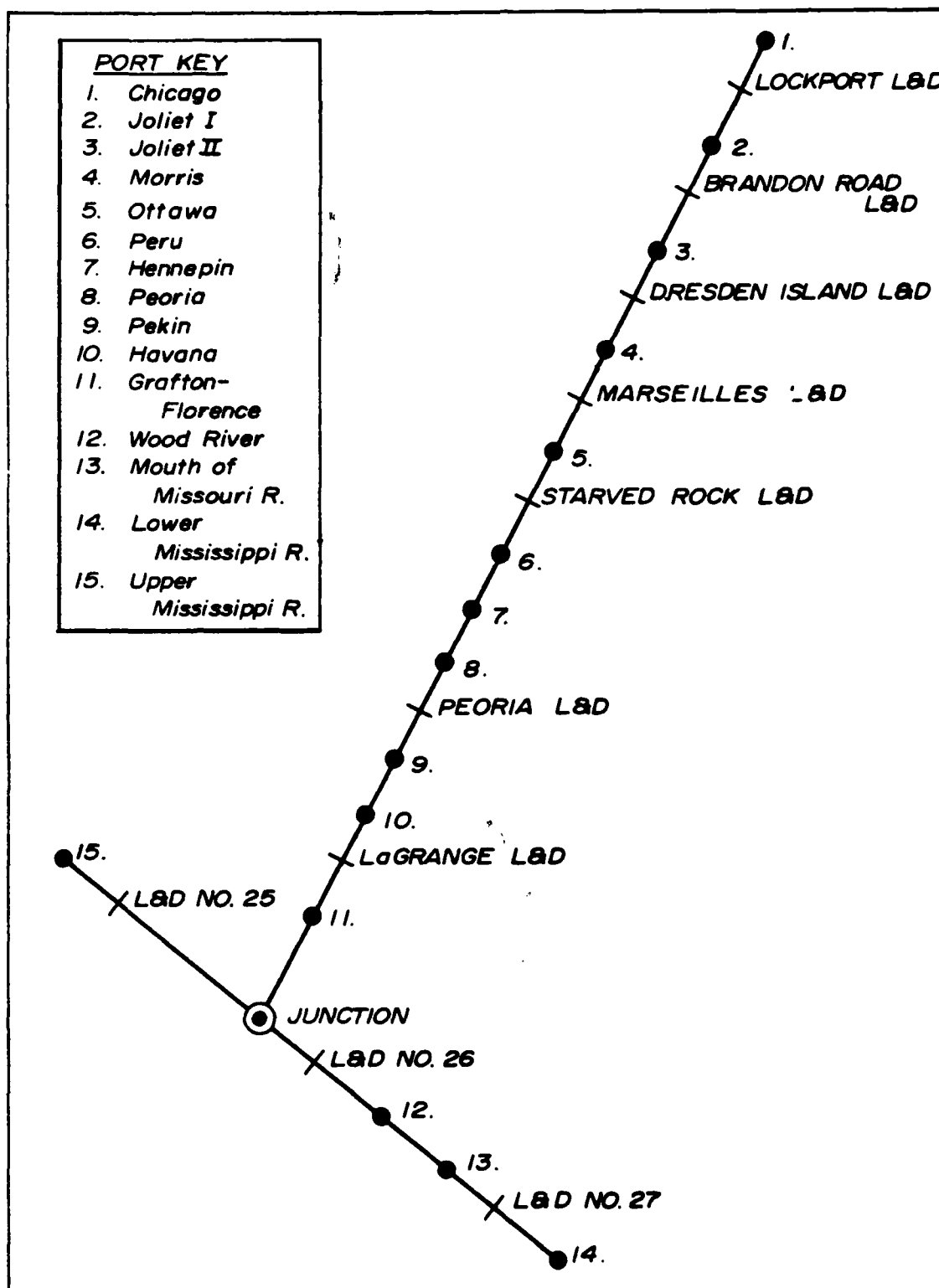


Figure 3-1 Illinois-Mississippi Ten-Lock Subsystem

confidence intervals, under the usual assumptions of normality and independence.

Simulation runs were then made for each alternative to be tested by modifying the appropriate 1968 data values, as will be described below. Hence, all runs simulated system operations for the year 1968. The three-printout format was retained, and again delay confidence intervals were calculated (based on only three observations, however). Comparison of corresponding confidence intervals, which is equivalent to the standard t-test for equality of means, was then used to ascertain which changes in average tow delay were statistically significant. Finally, those modifications which reduced delays the most were further tested by simulating their performance under projected 1980 demand conditions.

Experimental Design

Five simulation input factors were varied in this experiment, as summarized in Table 3.1. Although major emphasis was placed upon examining each factor in isolation, certain factorial combinations were also studied. The following paragraphs present the rationale for, and physical interpretation of, the specific experimental values selected for the investigation.

1. Flotilla Size

The fleet mix exhibited in the 1968 data was such that approximately 30-40% of all lockages required a double cut through a 600-foot-by-110-foot chamber. Limitation of flotilla size to that which would fit such a chamber in a single lockage was studied as an alternative to replacement of these chambers with larger structures. It was expected that elimination of multiple lockages would provide for smoother operations at the locks, decreasing significantly the probability of extremely long delays.

TABLE 3.1. SUMMARY OF EXPERIMENTS

VARIABLE	CALIBRATION CONDITIONS	EXPERIMENTAL VALUES
1. Flotilla Size	No Restriction	Single lockage in a 600-foot-by-110-foot chamber
2. Dedicated Equipment Percentages	50% - 100%	Zero
3. Locking Time Frequency Distributions	As Given	a) 15% reduction in mean b) 15% reduction in std. dev. c) both of above
4. Chamber Selection Penalty Cards	Allowed	Not Allowed
5. Traffic Load	1968	1980

2. Dedicated Equipment

Dedicated equipment percentage is a barge-related datum which is used as follows:

if P_k = dedicated percentage for barge type k ;

L_{ijk} = number of loaded type k barges originating at port i and terminating at port j ;

E_{ijk} = number of empty type k barges traveling from i to j ;

then

$$E_{ijk} \geq (L_{jik})(P_k)/100.$$

That is, the loaded barge movements are mirrored by the specified percentage of empty movements. The grossest inefficiency occurs when the dedicated equipment percentage for each barge type is 100. Conversely, the most efficient case would be when the dedicated equipment percentages are zero.

Only the dedicated equipment percentages for hopper barges were altered in this study; dedicated movements of integrated tows and other chemical and petroleum barges were retained as indicated in the data.

3. Locking Time Distributions

Lock operations are characterized in the simulation model by 15 time-frequency distributions. These time components are the following: long entry time; short entry time; single lockage; double lockage; triple lockage; set-over lockage; chamber swingaround time; and exit time. For each component except swingaround, data are required for both the upstream and the downstream directions, making a total of 15 components. If each of these distributions is characterized by a mean μ and standard deviation σ , then three changes can be made to increase the efficiency of lock operations. In the real world, these improvements could occur through changes ranging from an efficient lockmaster to increased sophistication in technology and overall systems control at locks, analogous to the traffic controls that now exist at airports.

The three types of frequency distribution modifications alluded to above are the following:

- (1) The means of distributions can be reduced with no change in the standard deviation. This would be representative of a situation where the lockage times are made more efficient through faster processing but no attempt is made to control random fluctuations, i.e., the spread in the lockage times remains the same.
- (2) In an exactly opposite case, the standard deviations of the distributions can be reduced with no change in the mean. Here, the randomness is controlled but no attempt is made to reduce average lockage times. The reason for this might be that in certain

cases it may be financially and/or physically feasible to implement one but not the other. That is, the cost of controlling randomness through some operating procedure may be nominal with respect to the installation of expensive machinery to reduce lockage times.

- (3) On the other hand, it may be feasible to reduce both the means and the standard deviations.

Figure 3-2 shows the modifications in the order listed above. The superscript prime (') is used to indicate the corresponding parameters of the modified distributions.

A mean reduction factor of 15% was used initially, as this was thought to be a reasonable goal. Hence, the distributions for all 15 operations at each lock were shifted such that $\mu' = 0.85\mu$. The 15% figure was retained for the standard deviation reduction, primarily because of convenience. Subsequently, runs were made with mean shifts of from 5% to 25% in 5% increments.

4. Chamber Selection Penalties

The simulation model also allows the user to control the distribution of lockages among designated chambers at multichamber locks, through penalty cards. For example, if a multiple chamber lock exists with a large chamber and a small chamber, real world conditions might dictate that the smaller chamber is rarely used. That is, the smaller chamber might be exclusively used for pleasure craft or for flotillas that could pass through it in a single lockage, or it might be reserved as an auxiliary chamber to be used only when the main chamber is out of operation. Such controls were in effect for the small (360 feet by 110 feet) chamber at L&D 26 for the model calibration runs.

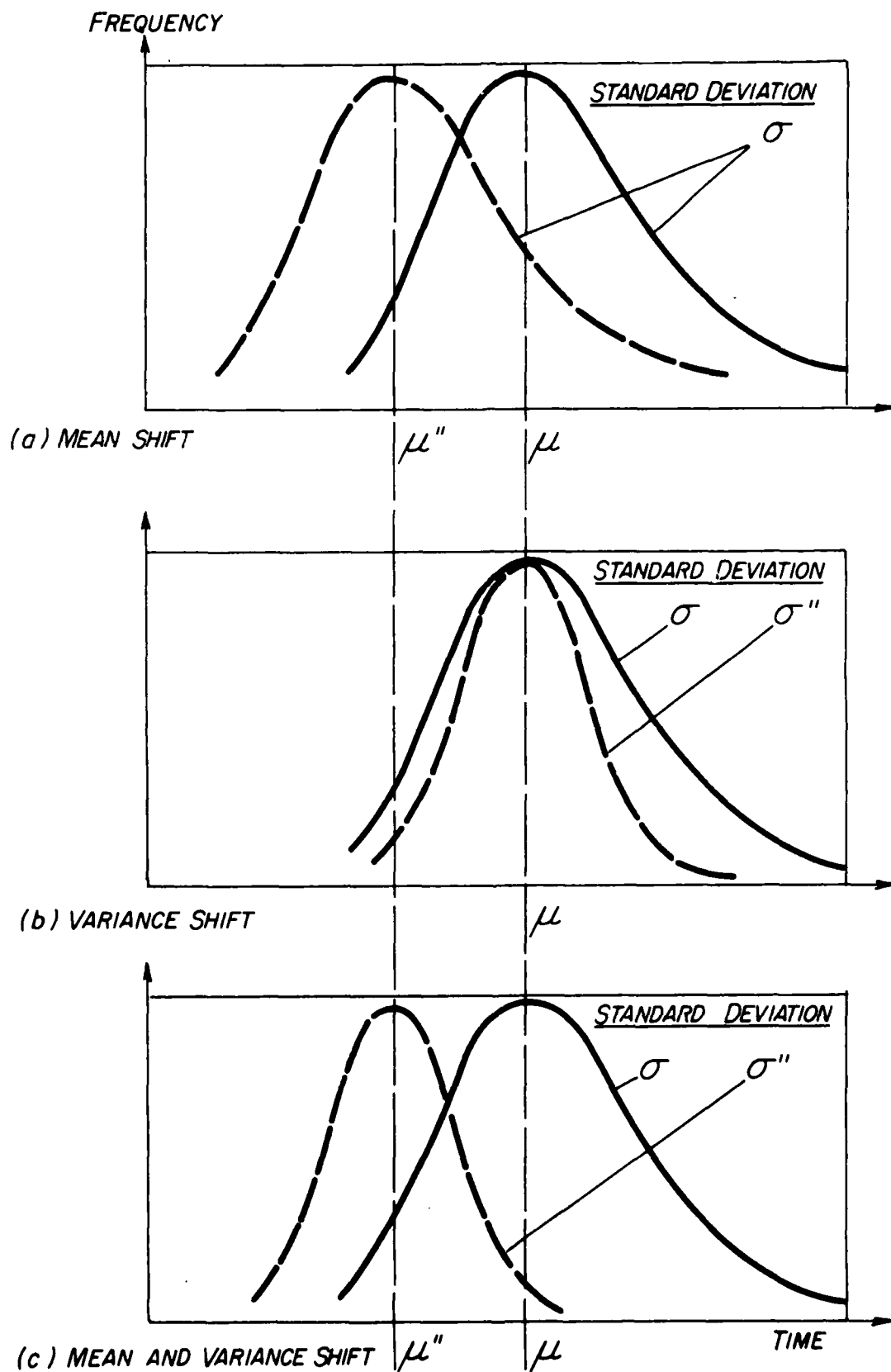


Figure 3-2 Modifications in Locking Time Frequency Distributions

The consequences of these rules are a higher utilization rate for the larger chamber, a correspondingly lower utilization rate for the smaller chamber, and an overall higher delay rate at the lock. Hence, through the removal of the penalty cards, i.e., relaxation of small chamber controls, the overall delays can be reduced. This would be a relatively easy change to implement and, in fact, is often used when the main chamber is in repair status. The effects of removing chamber selection controls at L&D 26 were studied in this experiment.

5. Traffic Load

In the initial study of the Illinois-Mississippi subsystem, the 1968 system was unable to service the demand expected in 1980, due primarily to the development of infinite queuing at L&D 26. Hence, it was thought that a good test of the more promising configurations emerging from the preceding experiments would be to subject them to the projected 1980 traffic load. Two such runs were made for the following factor combinations: (1) zero dedicated equipment, 15% reduction in mean and standard deviations; and (2) the preceding, plus flotilla size limitation.

6. Factor Combinations

The chief factor combinations tested involved crossing flotilla size limitation with all other factors, except for the chamber penalty factor. Also, the dedicated equipment factor was crossed with the three 15% locking frequency distribution shifts; and these three combinations were then crossed with flotilla size limitation. Table 3.2 lists the precise conditions which were input for each of the 26 simulation runs comprising the study.

TABLE 3.2. DESCRIPTION OF SIMULATION RUNS

SIM. NO.	DESCRIPTION OF EXPERIMENT
1	Flotilla size limitations only
2	Zero dedicated equip. percent. only
3	Lock freq. distributions, mean shift
4	Lock freq. distributions, std. dev. shift
5	Lock freq. distributions, mean and std. dev. shift
6	Penalty cards removed
7	1980 load with i) Flotilla size limit, ii) Zero ded. eq. %, iii) μ & σ shift
8	Flotilla size limit + mean shift
9	Flotilla size limit + std. dev. shift
10	Flotilla size limit + mean and std. dev. shift
11	Zero ded. eq. percent. + std. dev. shift
12	Zero ded. eq. percent. + mean shift
13	Zero ded. eq. percent. + mean & std. dev. shift
14	Flotilla size limit. + zero ded. eq.
15	Flotilla size limit. + zero ded. eq. + mean shift
16	Flotilla size limit. + zero ded. eq. + std. dev. shift
17	Flotilla size limit. + zero ded. eq. + mean and std. dev. shift
18	1980 load with i) Ded. eq. % = zero, ii) μ & σ shift
19	5% μ reduction only
20	10% μ reduction only
21	20% μ reduction only
22	25% μ reduction only
23	5% μ reduction + flotilla size limitation
24	10% μ reduction + flotilla size limitation
25	20% μ reduction + flotilla size limitation
26	25% μ reduction + flotilla size limitation

μ = Mean; σ = Standard Deviation

Results

The principal simulation output value of interest in this study was average delay per tow (ADPT) at each lock. It will be recalled that three samples were available for each run, corresponding to times of 18,000, 36,000, and 48,200 minutes. Values of ADPT and its standard deviation were calculated for each run and used to derive 95% confidence intervals as displayed in Table 3.3. The first line in the table gives the confidence intervals for the calibration runs. Since the conclusions drawn from the upstream values are the same as those drawn from the downstream values, only the latter are provided.

The results for the system as a whole, particularly the total system delay, are also revealing; and these are given in Table 3.4. Complete numerical results and a thorough interpretation of them are provided elsewhere [21].

Discussion of Results

1. Calibration Runs

The calibration runs, i.e., the initial six runs used to establish bench mark values for average tow delay, illustrate graphically the random variation inherent in simulation results. Based on a single run, for example, it might be concluded that in 1968 ADPT was higher at Brandon Road than at Lockport. As shown in the first line of Table 3.3, however, it is also quite possible for a different run to indicate the reverse situation; and, in fact, there is no statistically significant (at 95% confidence) difference in ADPT at the two locations.

These runs also showed that the length of the ADPT confidence interval is dependent upon the lock utilization rate. At utilization rates of

TABLE 3.3. 95% CONFIDENCE INTERVALS FOR ADPT (DOWNSTREAM)

SIM. NO.	AVERAGE DELAY PER TOW (MIN.) ^a									
	Lockport	Brandon Road	Dresden	Marseilles	Starved Rock	Peoria	LaGrange	L&D 25	L&D 26	L&D 27
Calibration	61-99	83-144	23-31	38-41	27-38	33-49	27-37	12-17	107-136	1-3
1	7-109	19-83	8-20	0-34	6-14	(-10)-65	6-20	5-13	61-213	0-4
2	21-75	19-113	14-42	(-13)-76	(-4)-57	10-78	18-34	8-42	53-201	(-1)-6
3	(-15)-96	(-85)-250	(-18)-65	(-6)-71	8-28	(-7)-58	10-30	(-4)-31	33-95	0-2
4	(-50)-209	(-218)-524	(-3)-60	15-63	(-14)-85	(-7)-84	13-43	(-5)-34	83-165	2-2
5	(-2)-77	(-91)-256	(-17)-64	1-55	7-29	7-37	13-27	(-9)-32	14-126	0-2
6	(-56)-211	(-226)-536	(-9)-54	25-69	3-53	(-10)-95	16-46	(-2)-33	10-50	(-1)-6
7	18-198	(-35)-184	7-25	6-40	4-26	(-8)-61	5-19	4-34	224-314	3-7
8	1-65	20-32	5-13	(-4)-25	(-2)-17	12-16	6-14	(-3)-18	23-111	0-2
9	0-111	39-63	(-1)-34	(-2)-31	4-20	13-27	9-21	(-3)-30	67-211	0-4
10	7-61	16-40	0-16	0-21	(-1)-16	7-17	5-15	(-5)-22	31-101	0-1
11	29-68	22-102	26-46	11-43	5-55	13-71	18-30	9-45	58-218	(-1)-6
12	12-42	23-57	3-33	1-33	(-6)-43	(-7)-72	18-26	9-23	21-133	0-1
13	17-41	11-65	8-26	9-23	(-11)-48	(-2)-67	16-24	2-22	38-112	1-1
14	17-105	39-61	0-27	14-26	10-18	13-29	2-24	2-14	116-202	0-2
15	12-66	12-46	0-17	7-11	3-15	11-15	0-15	3-5	61-91	1-1
16	21-93	39-51	(-3)-28	7-19	(-3)-34	13-27	3-19	2-12	129-177	0-1
17	12-64	12-46	0-18	7-15	0-20	7-17	2-12	1-9	56-104	0-0
18	(-64)-571	37-177	34-76	30-80	37-53	44-124	20-50	7-61	129-395	0-7
19	(-10)-133	79-105	5-45	(-7)-68	24-40	7-53	18-34	0-24	20-182	0-4
20	(-2)-113	25-105	8-36	5-43	21-31	3-43	14-32	0-24	8-160	(-1)-4
21	(-10)-93	29-61	11-21	(-2)-45	7-31	1-31	8-36	4-14	(-4)-107	0-2
22	(-11)-74	8-64	2-18	(-5)-42	8-26	1-27	7-23	(-1)-20	4-66	0-2
23	6-84	24-54	1-19	(-3)-30	0-18	11-23	7-21	(-8)-27	33-151	0-2
24	1-75	24-34	0-22	(-8)-37	0-22	12-16	8-16	0-17	18-122	0-1
25	7-43	10-36	0-12	3-11	0-13	5-13	5-7	0-10	20-74	0-1
26	1-37	8-28	(-1)-12	2-12	0-10	3-11	7-7	1-5	21-43	0-1

^aNegative values are theoretical only and indicate that the actual distribution of delay values is skewed.

TABLE 3.4. SYSTEM DELAY VALUES

Sim. No.	Total Delay (Hours)	No. Tows Delayed	Average Delay/Tow Delayed (Minutes)
Calibration Runs	3800.92	2187	103
1	4109.48	2980	82
2	2956.60	1899	93
3	2376.18	1935	73
4	4080.15	2268	107
5	2394.02	1919	74
6	2948.55	2027	87
7	11937.70	6139	116
8	2189.03	2553	51
9	4076.28	3031	80
10	2166.50	2563	50
11	2990.05	1892	94
12	1802.97	1593	67
13	1759.38	1580	66
14	4327.11	2935	88
15	2270.58	2493	54
16	4217.70	2911	86
17	2382.57	2545	56
18	11367.38	4420	154
19	3131.37	2065	90
20	2646.72	1986	79
21	1821.87	1731	63
22	1460.68	1612	54
23	2965.72	2811	63
24	2399.17	2666	53
25	1606.87	2340	41
26	1221.85	2105	34

less than 50%, very tight 95% confidence intervals, on the order of $\pm 15\%$ of the mean, were obtained. At higher utilizations, however, less precision is achievable, $\pm 30\%$ of the mean being a typical interval.

2. Variance Reduction

It is known from queuing theory that mean delay is a function of both the utilization rate and the variance of the service distribution, that is, the variance of the locking times. The simulation results, however, indicated that reducing the variance of the locking time components did not reduce ADPT. This is so primarily because the tow fleet was not homogeneous. That is, the existence of double and triple lockages is the main contributor to the variance of average processing time, regardless of any change in the variance of the individual locking time components. Also, the multistage Monte Carlo sampling technique used in selecting locking component times in the model makes it difficult to input any preselected reduction in service time variance, even when the fleet composition is controlled. Hence, the main significance of these findings is that the simulation results appear to be insensitive to the dispersion in the locking time-frequency distributions.

3. Dedicated Equipment

The simulation runs also indicate that dedicated equipment percentage is not a crucial factor. The reduction in number of tows, made possible by simulating zero dedicated equipment percentages, did not significantly alter delays at locks. Significance, of course, refers to results of statistical tests; and whether these results are the only consideration is a matter of judgment. But both the t-test and a more powerful analysis of variance test indicated that dedicated equipment percentage was not a significant factor at the .05 level of α .

It should be noted, however, that this measure (Simulation No. 2) reduced total delay by more than 22%. That is, although ADPT was unaltered, there were fewer tows incurring this delay. Hence, it would appear that greater interline barge utilization by the towing industry would produce some tangible benefits.

4. Chamber Selection Penalty

Elimination of the penalty card at L&D 26 did result in satisfactory values for delays, indicating that a greater use of the auxiliary chamber for commercial tows during heavy traffic periods might be desirable.

5. Flotilla Size Limitation

The two most significant factors investigated in this study were flotilla size limitation and a reduction in mean locking times. Both were found to be significant by statistical tests at the .05 level of α . With flotilla size limitation alone, reductions in average delay of the order of 20% were obtained. But the effect of flotilla size limitation at different traffic levels must also be considered.

The calibration runs produced 3801 hours of total system delay and 2187 tows delayed. With the introduction of flotilla size limitation at this 1968 traffic level, the total delay increased to 4109 hours and the number of tows delayed increased to 2980. The increase in the number of tows is consistent with prior expectations that flotilla size limitation would require more tows to carry the same amount of tonnage; but the increase in total delay was entirely due to L&D 26 which had a dense inter-arrival distribution.

But what happens at higher traffic levels? It is the generally accepted assumption, and not an unreasonable one, that the size of tows will

gradually increase with time to accommodate the increase in waterborne commerce. This would mean, for example, that in 1980 there would be more double lockages than in 1968. Presumably, therefore, flotilla size limitation would be a more significant factor in 1980 than in 1968. The question, then, is: Does the elimination of a large number of double lockages (triple lockages as well) in 1980, with the resultant decrease in expected locking time, compensate for the increase in tows required to carry the 1980 commodity flows?

It is difficult to answer this question conclusively from the two 1980 simulation runs available. In comparing total delay values, the run with flotilla size limitation had lower total delays at every lock except L&D 26 and L&D 27. In fact, this run had a higher system total delay almost entirely due to L&D 26. The reason for this behavior at L&D 26 can be traced to that found in the 1968 runs, namely, a highly skewed inter-arrival pattern.

It is more productive, therefore, to consider the fact that with flotilla size limitation, the 1980 traffic could be borne satisfactorily by the system (except for L&D 26 where delays of four to five hours were incurred), but in its absence there was partial, if not complete, collapse. Flotilla size limitation reduces not only total delay (allowing for the exceptions), but also the dispersion in the delay values, thus preventing large queues from building up. By making flotilla sizes more uniform, it makes the expected locking times uniform³ and hence the delay values uniform. In other words, the expected delay for a tow approaching a lock becomes

³Note that this relationship confirms prior expectations that reducing locking time variance should reduce delays, a point not borne out in the variance reduction run.

almost strictly a function of the number of tows already present at the lock and not of the size of any tow (or chamber except for L&D's 26 and 27 which have multiple chambers).

This fact becomes very crucial as the traffic level in the system goes up. With very dense traffic, a tow with a large expected locking time, such as one requiring double or triple lockage, can start a chain reaction magnifying the waiting times and creating heavy congestion at the locks. Flotilla size limitation reduces both the mean and the variance of expected delay time by reducing and standardizing the locking times, and thereby keeps the system functioning rather smoothly.

These results also indicate that the delay values predicted by the simulation model are sensitive to the flotilla size data. This sensitivity cannot be measured precisely, in that only two points are available (i.e., present fleet mix vs. all single lockages). However, it is expected that delays will increase or decrease as the proportion of multiple lockages increases or decreases.

6. Reduction in Mean Processing Times

The second significant factor, a reduction in mean locking times, is perhaps easier to implement than flotilla size limitation; and the simulation results are highly sensitive to it. This fact is illustrated by Figure 3-3, which plots ADPT for the system against mean tow processing time. The latter values were obtained by dividing total system lock processing time by total system lockages; hence, the curves are not strictly applicable to any given lock. Nonetheless, they do give a good indication of what percentage reduction in ADPT can be expected for a given percentage reduction in mean locking time.

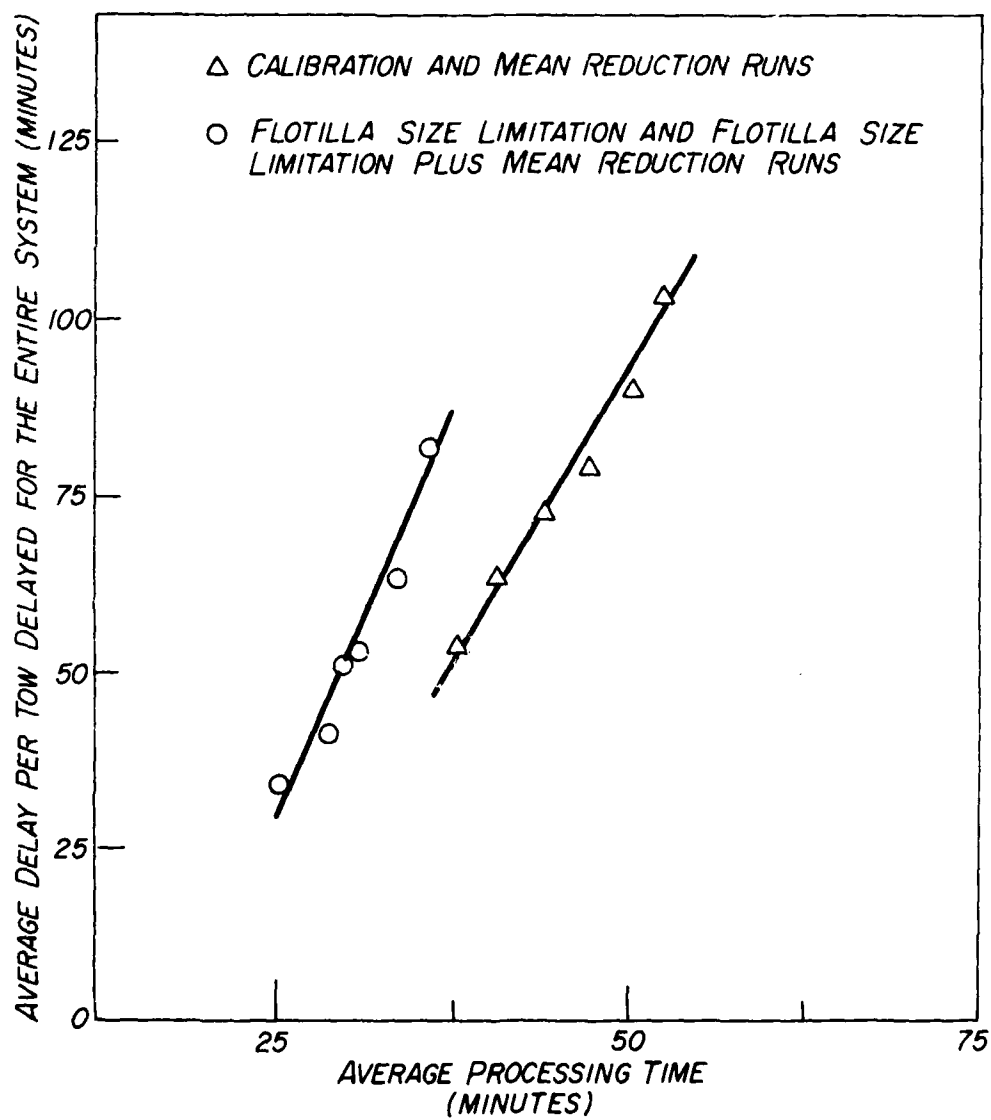


Figure 3-3 System Delay Curves for Reduced Mean Locking Times

It is also instructive to consider these results in terms of what the equivalent capacity increase is for a given reduction in locking time. This can be approximated as follows:

Let

TD_1 = existing total delay in the system;

TD_2 = total delay for a higher level of traffic, say T_2 ;

T_1 = existing total number of tows in the system;

T_2 = higher number of tows.

Suppose a k_1 percent reduction in locking times is implemented, yielding a p_1 fraction reduction in average delay per tow. Then, how much more traffic can the system handle with TD_2 no greater than TD_1 ?

Let

$ADPT_1$ = average delay per tow for the existing system;

$ADPT_2$ = average delay per tow for the system with k_1 percent reduction in locking times;

$$ADPT_1 = \frac{TD_1}{T_1} \text{ by definition;}$$

$$ADPT_2 = \frac{TD_2}{T_2} \text{ by definition;}$$

$$ADPT_2 = (1 - p_1) \times ADPT_1; \text{ from specification above.}$$

Therefore,

$$\frac{TD_2}{T_2} = (1 - p_1) \frac{TD_1}{T_1},$$

$$\text{or } T_2 = \frac{T_1}{(1 - p_1)}.$$

As an illustrative example, for $k_1 = 25\%$ reduction in locking times, $P_1 \approx 0.5$. Therefore, $T_2 = \frac{1}{(1 - .5)} T_1 = 2T_1$. The system can handle twice as much traffic as that in 1968 and produce comparable delays, if locking times are reduced by 25%.

Now consider the simulation runs with flotilla size limitation in combination with reduction in locking times. The additional tows produced due to the former effect distort the ability to use ADPT as the basis of comparison. It is reasonable, however, to look at average delay per ton, as follows:

Let TD_1 and TD_2 be defined as previously, and

TON_1 = existing total tonnage in the system;

TON_2 = higher tonnage.

If the average delay per ton for the two systems is to be the same, then

$$\frac{TD_1}{TON_1} = \frac{TD_2}{TON_2}$$

For the simulation run with flotilla limitation and 25% reduction in locking times, the total delay was reduced by approximately 68%. In other words, $TD_2 = (1 - .68) TD_1$ or $TD_2 = .32TD_1$. To derive the higher traffic that can be handled if TD_2 were equal to TD_1 ,

$$\frac{TD_1}{TON_1} = \frac{TD_2 / .32}{TON_2}, \text{ and if } TD_1 = TD_2, \text{ then}$$

$$TON_2 = \frac{1}{.32} TON_1 = 3.1 TON_1.$$

With flotilla limitation and 25% reduction in locking times, the system capacity can be increased to about three times the 1968 traffic, while still achieving comparable total delay and average delay per ton.

Conclusions

The main findings of this study are summarized as follows:

- (1) The limitation of flotilla size to that of a single lockage in a 110-foot-by-600-foot chamber resulted in 20% reductions in ADPT throughout the system. This factor, however, became even more crucial with higher traffic levels, because it not only reduces the processing times at locks but also makes the times more uniform; i.e., it reduces the variance of the lock processing times. It is this combination of faster and more uniform locking times that enables a system to function adequately at high traffic levels.
- (2) The use of zero dedicated equipment percentages resulted in statistically insignificant reductions in average delays. Simulated system operations, therefore, are insensitive to dedicated equipment percentages. Total system delay, however, does vary with this factor.
- (3) A 15% reduction in the means of the locking times resulted in 30% to 40% reductions in delays. The system was also found to be highly sensitive to other reductions in mean locking times.
- (4) A 28% reduction in the variance of the locking time frequency distributions had no significant effect on delays. This is due primarily to the overwhelming influence of multiple lockages on processing time variance.
- (5) Of all the configurations tested, the combination of flotilla size limitation and 25% reduction in locking times had the greatest effect, resulting in about 66% reduction in delay through the system. In terms of system capacity, this configuration enabled

the system to accommodate approximately three times the 1968 traffic, while still producing comparable delays.

- (6) A heavier traffic load for the year 1980 was borne adequately when some of the principal factors mentioned above were incorporated into the system.
- (7) The desirability of obtaining as many replications as possible in order to establish statistically meaningful simulation results was confirmed. Analysis of variance was found to be useful for obtaining more power when numerous replications are not available.
- (8) The method of establishing confidence intervals for the main variables of interest as a calibrated basis of comparison for ascertaining the effects of each alternative was concluded to be a valuable tool in simulation analysis. The confidence intervals could also be used to estimate the precision of a subsequent cost-benefit analysis.
- (9) The inland waterway simulation model is well suited to the analysis of potential nonstructural improvements to a waterway system, since delays predicted by the model are sensitive to variations in the main controllable system elements.

IV. SIMULATION EXPERIMENTS: SINGLE LOCK STUDIES

This chapter describes a series of experiments performed using the single-lock simulation model developed by PTTSC for the Corps of Engineers. This multiple-chamber single-lock model, LOKSIM, was first developed during the 1970-71 year at PTTSC; and its features and initial testing were reported in August of 1971 [22]. During the past year the model has undergone many changes and modifications which are reported in the most current LOKSIM report [23].

LOKSIM is a multipurpose computer simulator of a multiple-chamber lock on the inland waterways system. It has developed into a very general model which can be used to simulate a variety of conditions which may exist at a single lock. The structure of the FORTRAN program utilizes many subroutines in order to facilitate changes to the logic with a minimum effect upon the remaining program. This modular features enables a knowledgeable user to alter the model operation by substitution of these "logic blocks" without disturbing the larger program.

The purpose for developing the LOKSIM model was to provide a simulation tool which could be used in investigating single lock operation under a variety of pleasure craft volumes, commercial tow volumes, and lock operating rules and characteristics. As congestion at a particular lock increases, the way in which the traffic is handled becomes increasingly important in predicting the length of delay incurred at the lock. Simulation of a single lock is an attractive and effective means for studying such problems.

Three factorial simulation experiments were performed using the LOKSIM model within the past year. The initial experiment tested four service disciplines over four tow volume loadings. The second investigation looked

at the effects of high pleasure craft volumes at the lock, while the final experiment considered the question of separated-versus-adjacent chambers.

Objectives of the Study

The objectives of the experiments were to:

- (1) exercise the model under a variety of situations in order to expose and correct any logic errors remaining in the program. Only when very special cases occur within the model do certain logic branches become utilized; and the hope was that by pushing the model to its limit in some instances, these branches would be taken and could therefore be checked out.
- (2) test four alternative service rules at a typical inland waterway lock under a range of tow volume loadings.
- (3) examine the effects of pleasure craft volumes on commercial tow delay within the LOKSIM structure.
- (4) evaluate what effects the separation of chambers had on the lock operation in terms of delay to tows.

Experimental Design

1. Experiment I

A dual-chamber system consisting of a 1200-foot-by-110-foot chamber adjacent to a 600-foot-by-110-foot chamber was simulated in the first experiment. Service times were generated from data collected previously at L&D 27 on the Mississippi River by increasing all the locking times by about 40%. (This increase was warranted when a pilot run failed to reach the high utilization rate which was desired for the experiments.) By making use of one of the input capabilities, penalty cards, the system was able to be operated in such a way that any double lockages were effectively

prevented from occurring in the small chamber of the system. This assumption is in line with current operations at some locks and dams on the inland system. No pleasure craft were to be locked at the simulated lock in Experiment I.

A constant mix of lockage types was used in the tow lists insuring that the percentages of singles, doubles, and setovers (in a 600-foot chamber) would remain the same over the four volume levels. For all tow volumes, the mixture of lockage types remained at 52% single lockages, 28% double lockages, and 20% setovers when considered against a 600-foot-long chamber.

Experiment I was a two-factor experiment which crossed tow volume with service disciplines. The first factor, tow volume, had four levels of tow arrivals: 10.42 tows/day, 19.20 tows/day, 28.18 tows/day, and 36.62 tows/day. The second factor, the service discipline, also had four levels. The first level was a first-come-first-serve tow choice rule followed by an expected completion time chamber choice rule. The second level of the service discipline factor involves simulating a lock which used a 3-up - 3-down tow choice rule in conjunction with an expected completion time chamber choice rule. The third level served opposing queues alternately to achieve a kind of flip-flop procedure. The final level or method in which the lock was operated, was the equalized queue tow choice method. This method involved choosing tows from the queue at the lock which was the longest and assigning them to a chamber by the minimum expected completion time.

The average delay per tow (ADPT) was chosen as the response variable or performance measure. This ADPT was the average delay across both directions and for both chambers.

A simulation period of 25,000 minutes and a warm-up period of 5000 minutes were used for all the simulation runs. The lengths were chosen in light of the findings of Desai [8]¹ and proved to be quite satisfactory. An interim printout time of 500 minutes was used which produced 50 observations of the locking system for each cell of the experimental matrix.

2. Experiment II

The second experiment was designed to satisfy Objective 3, which was to explore the relationship between pleasure craft volume and delays incurred by commercial tows. Therefore, the pleasure craft volume factor was crossed with the tow volume factor in a 4 x 3 design.

The lock system and configuration which was simulated remained the same in Experiment II as was described in Experiment I. The 600- and the 1200-foot chambers both operated under the same locking times with the same penalty restrictions employed. Only one service discipline was used in this second experiment, however, the serve opposing queues alternately (SQQA) rule. The length of the simulation, output specification, and the tow mix were all identical between Experiments I and II.

The levels of the first factor, tow volume, were identical to those used in Experiment I. The second factor, pleasure craft volume, was varied between no pleasure craft, 28.8 pleasure craft arrivals per day, and 50.0 pleasure craft per day.

3. Experiment III

The final experiment was performed to respond to Objective 4, which called for the measurement of the effect of chamber separation on tow

¹See also Chapter II above.

delay. The first factor, tow volume, is the common one throughout all the testing but in this third experiment it was crossed with chamber separation. The SOQA service rule was used, and no pleasure craft were permitted to lock through in this experiment. The second factor of this final experiment was simply either the separation or nonseparation of the two chambers in the system. The theory which justifies separated chambers leads one to predict lower delays for the separated chambers, due to a decrease in entering and exiting interference of the tows.

Results

1. Logic Correction

A total of 28 simulations were run for all the experiments using almost all the service rules within the model and over a wide range of tow and pleasure craft volumes. Only 28 runs were required since some of the experimental cells were repetitious between experiments. Of these 28, one run terminated due to a logic error. The high volume and 3-up - 3-down service rule created an unusual circumstance in the queue discipline section which was not provided for in the model, and the run terminated unexpectedly. This logical branch was provided, and the run completed.

2. Experiment I

The response variable for all the experimentation was average delay per tow. The mean values of ADPT for the 16 cells of Experiment I are tabulated in Table 4.1.

Graphically, the results of Experiment I are shown in Figure 4-1. Visual interpretation of the graph shows that the most significant differences in delays between disciplines occur at the highest volumes which

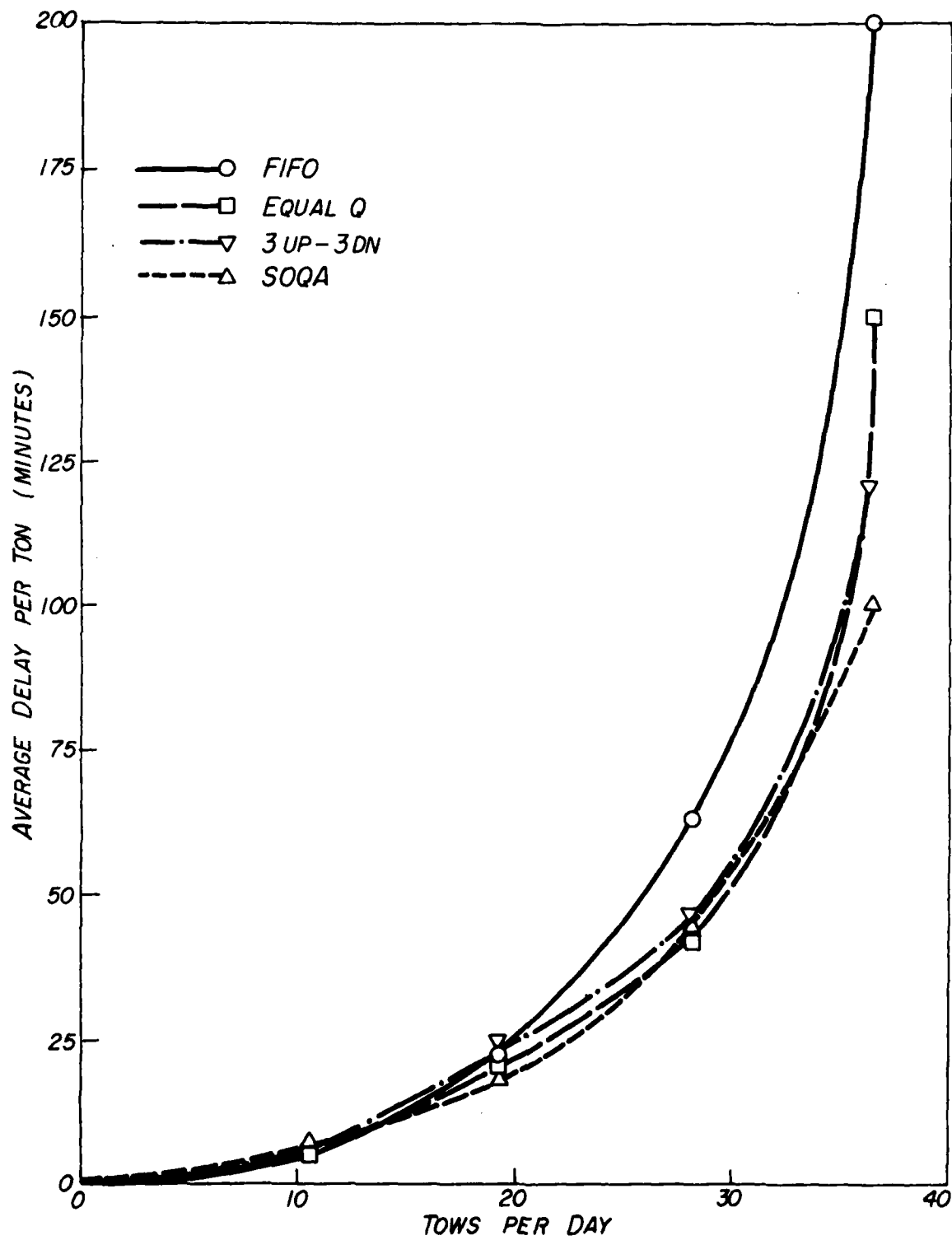


Figure 4-1 Experiment I Results

TABLE 4.1. NUMERICAL RESULTS: EXPERIMENT I

<u>Cell Number</u>	<u>Description</u>	<u>ADPT (minutes)</u>
I1	FIFO, Low tow volume	4.78
I2	FIFO, Medium tow volume	21.78
I3	FIFO, High tow volume	62.64
I4	FIFO, Very high tow volume	199.02
I5	3 up - 3 dn, Low tow volume	4.62
I6	3 up - 3 dn, Medium tow volume	23.20
I7	3 up - 3 dn, High tow volume	45.72
I8	3 up - 3 dn, Very high tow volume	120.18
I9	SOQA, Low tow volume	7.28
I10	SOQA, Medium tow volume	17.74
I11	SOQA, High tow volume	43.50
I12	SOQA, Very high tow volume	99.74
I13	Equal-Q, Low tow volume	4.62
I14	Equal-Q, Medium tow volume	20.82
I15	Equal Q, High tow volume	42.10
I16	Equal Q, Very high tow volume	150.14

substantiates an initial premise of the experiment. In addition, it would seem that the FIFO adds considerably to the average delay per tow at the two higher volume levels.

3. Experiment II

The second investigation centered on the determination of the effect of pleasure craft on delays experienced by commercial tows. Table 4.2 gives the results of the simulation runs made to model various tow volumes crossed with three pleasure craft volumes.

TABLE 4.2. NUMERICAL RESULTS: EXPERIMENT II

<u>Cell Number</u>	<u>Description</u>	<u>ADPT (minutes)</u>
I9	Low tow volume, No pleasure craft	7.28
II0	Med tow volume, No pleasure craft	17.74
II1	High tow volume, No pleasure craft	43.50
II2	Very high tow volume, No pleasure craft	99.74
III1	Low tow volume, 28.8 pleasure craft/day	18.50
II2	Med tow volume, 28.8 pleasure craft/day	34.48
II3	High tow volume, 28.8 pleasure craft/day	71.94
II4	Very high tow volume, 28.8 pleasure craft/day	145.32
II5	Low tow volume, 49.8 pleasure craft/day	22.90
II6	Med tow volume, 49.8 pleasure craft/day	39.80
II7	High tow volume, 49.8 pleasure craft/day	87.26
II8	Very high tow volume, 49.8 pleasure craft/day	178.86

Figure 4-2 shows the graphical results of Experiment II by plotting the tow volume against ADPT for the three levels of pleasure craft volume. The general shapes of the curves are very similar and, as expected, take the form of any volume-versus-delay curve. One difference in the top two lines is that they are not asymptotic to zero delay as the tow volume is decreased to zero. This follows naturally if one realizes that the delay expected for a single tow arriving at a lock which serves only pleasure craft is equal to the expected delay of the pleasure craft--not zero.

The same values are plotted in a slightly different manner in the graph shown as Figure 4-3. Instead of each line representing a pleasure craft volume level as in the previous figure, Figure 4-3 uses tow volumes

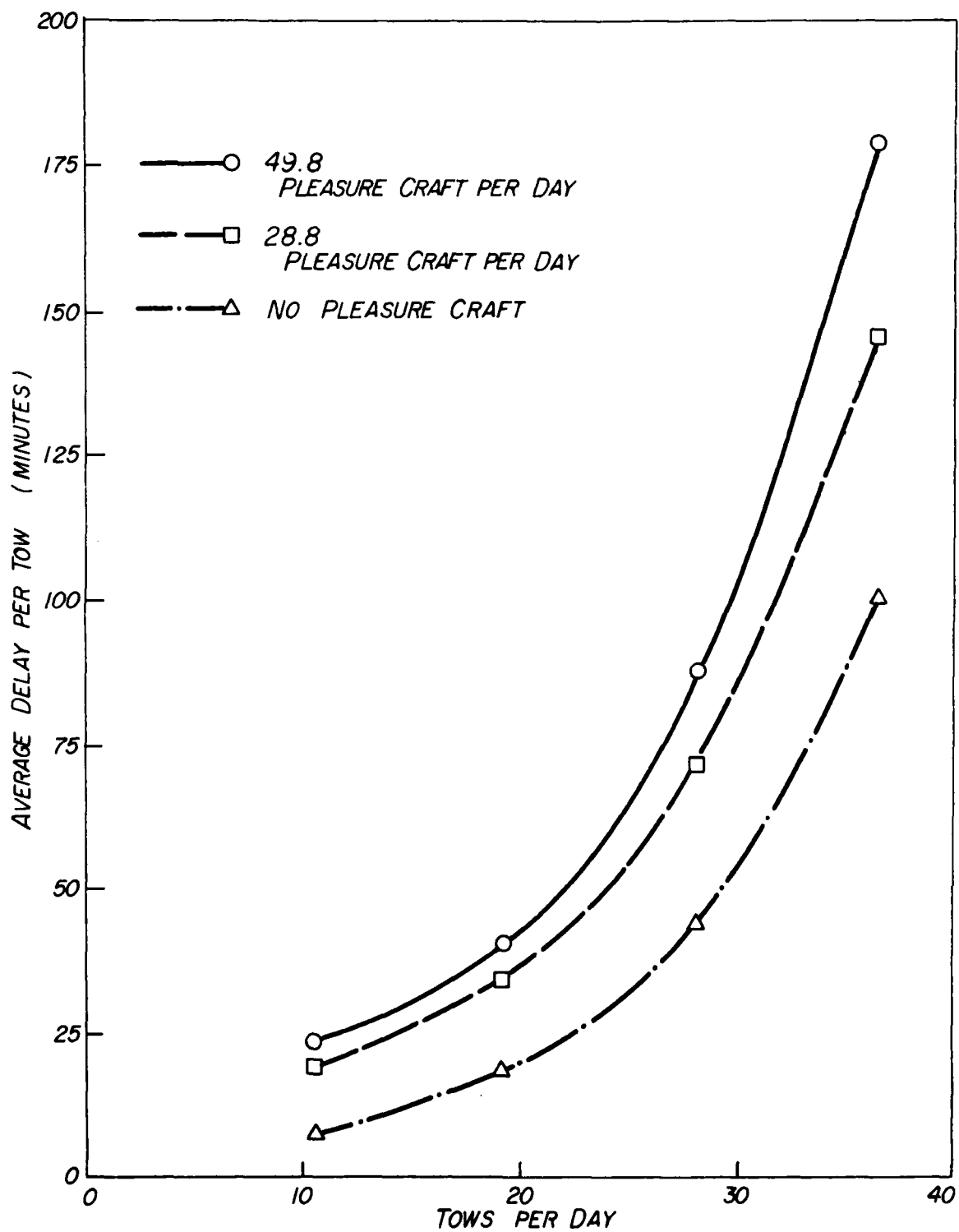


Figure 4-2 Experiment II Results

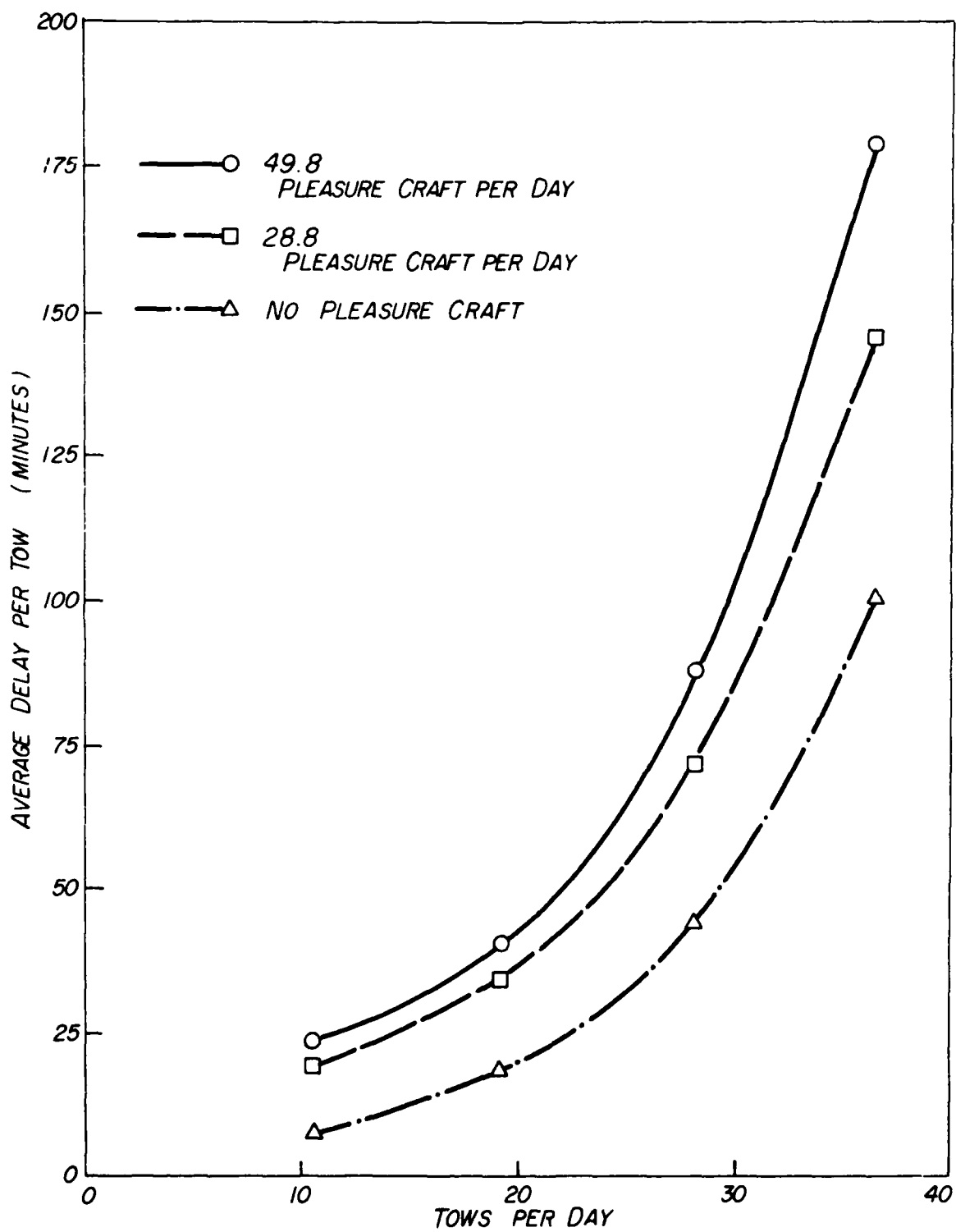


Figure 4-2 Experiment II Results

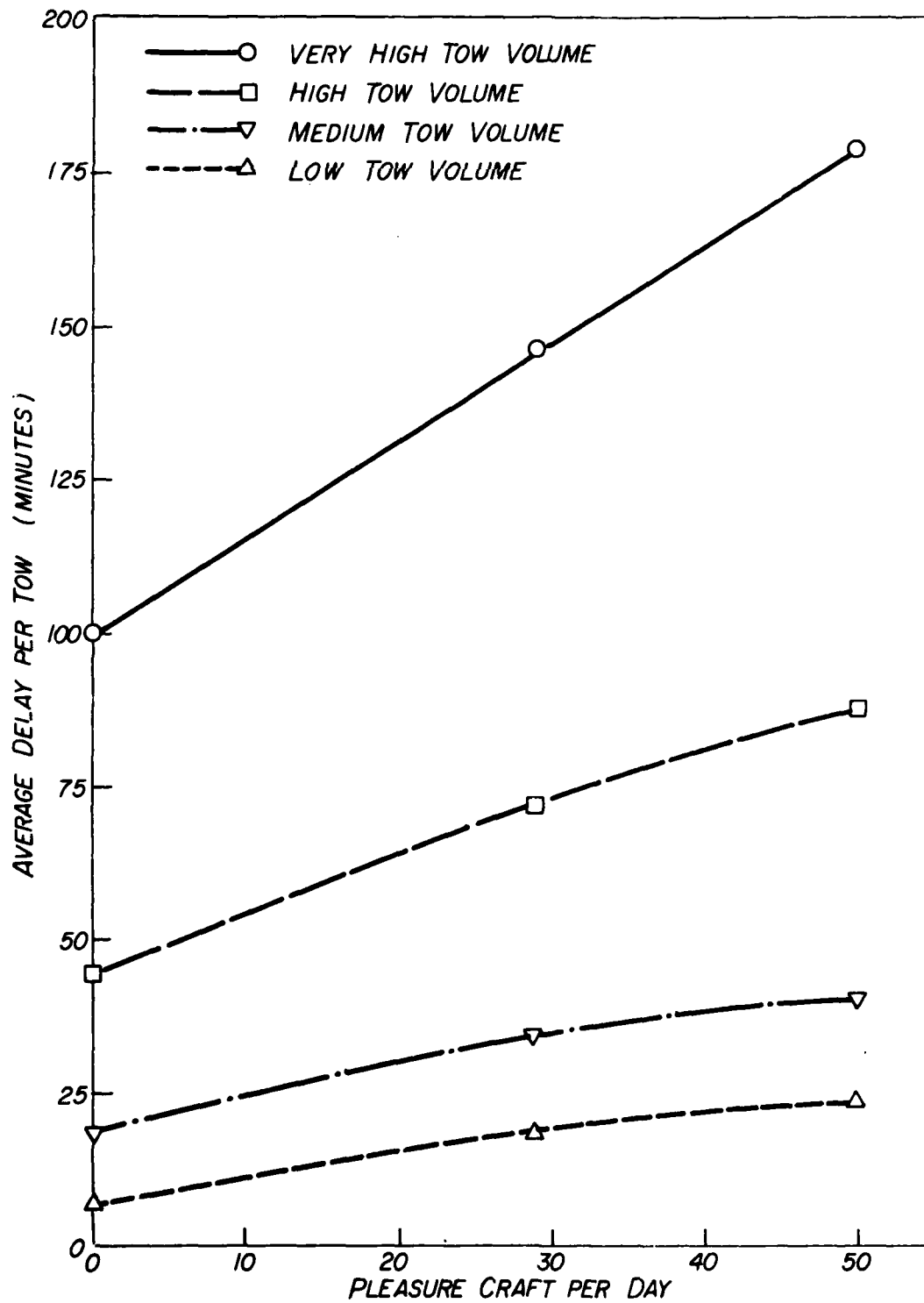


Figure 4-3 Experiment II Results Replotted

as its family of curves, and pleasure craft volume is shown on the abscissa of the plot. This graph shows an almost linear relationship between pleasure craft volume and average delay per tow, the linearity becoming more pronounced as the tow volume is increased. In addition, the slopes of the lines become increasingly steeper as the tow volume becomes larger.

4. Experiment III

The final experiment dealt with the problem of separated-versus-adjacent chambers at a lock. In Table 4.3 below, the mean delays of the two types of systems are shown.

A difference between mean delay values is present only at the two higher levels, and even then it is very slight. At the very high volume level, the ADPT is reduced by 3.58 minutes per tow when the chambers are separated for the particular system simulated. The graphs of the delay-versus-volume shown in Figure 4-4 demonstrate this slight difference even more clearly. It should be observed that the vertical or delay scale of Figure 4-4 is twice that of any previous delay curve in order that the difference would be visible.

TABLE 4.3. NUMERICAL RESULTS: EXPERIMENT III

<u>Cell Number</u>	<u>Description</u>	<u>ADPT (minutes)</u>
I9	Adjacent, Low tow volume	7.28
II0	Adjacent, Medium tow volume	17.74
II1	Adjacent, High tow volume	43.50
II2	Adjacent, Very high tow volume	99.74
III1	Separated, Low tow volume	7.28
III2	Separated, Medium tow volume	17.74
III3	Separated, High tow volume	43.38
III4	Separated, Very high tow volume	96.16

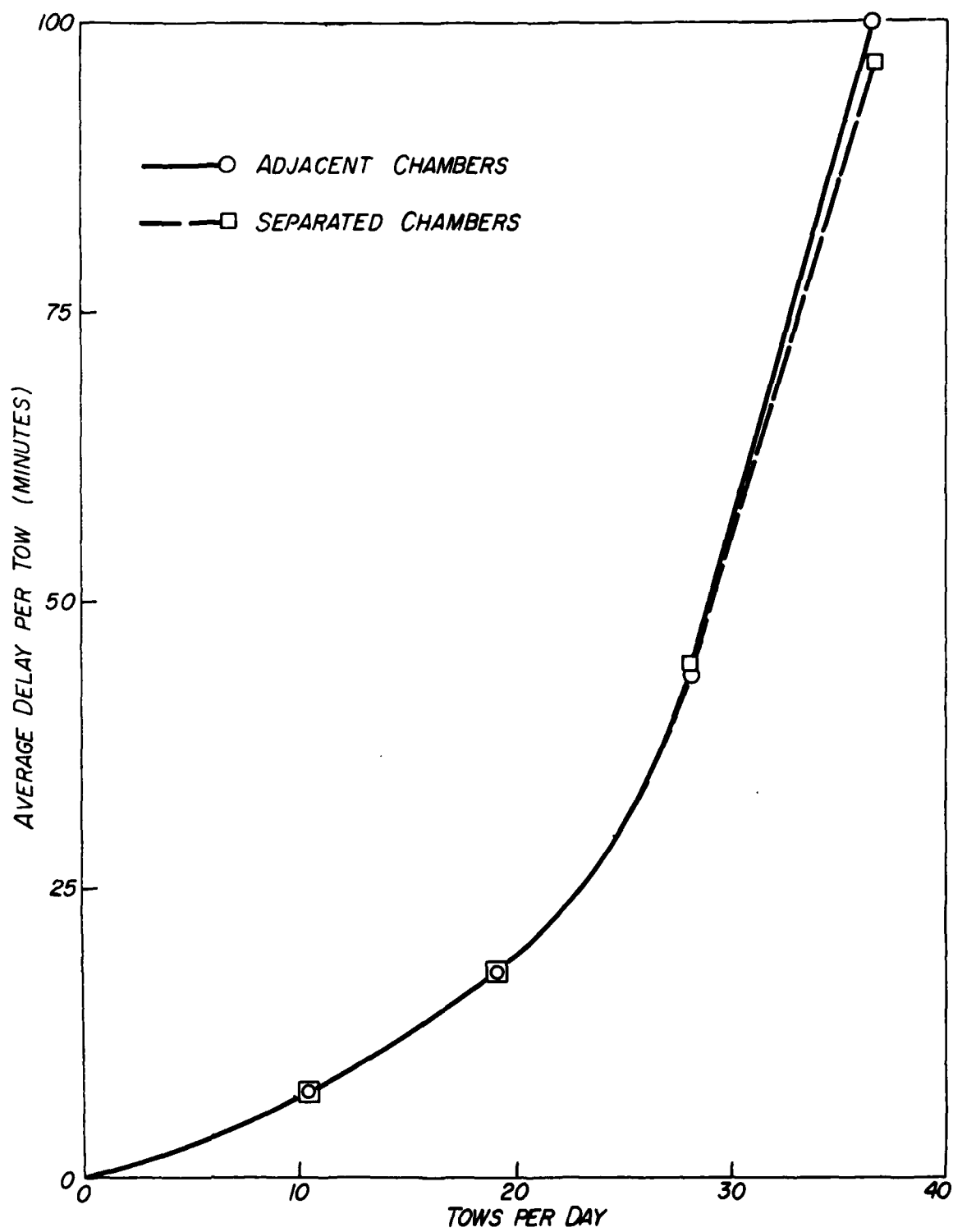


Figure 4-4 Experiment III Results

5. Analysis of the Three Experiments

A modified analysis of variance procedure (AOV) was carried out to investigate the statistical significance of the experimental results. The theoretical background and justification of this modified AOV technique are fully explained by Rao [19]².

Essentially, the independent observations were changed from 50 to 50, 45, 40, and 30 for the four increasing tow volume levels to account for autocorrelation in the data. This adjustment reduced effectively the degrees of freedom which were used in each analysis of variance. While all 50 observations were used for each cell and the sum of squares computed on that basis, the mean square error term was adjusted upward through use of equivalent degrees of freedom. The results of the AOV tests are shown in Table 4.4.

The interpretation of these AOV results is that for Experiment I, the different service disciplines do significantly affect the mean times, as does an increase of pleasure craft volume in Experiment II. Chamber separation is insignificant, however, at the 10% level over all the volumes. The AOV shows that the tow volume does affect mean delay (as well it should) in all three experiments. The interaction between service disciplines and tow volume is significant, which means that different disciplines affect increasing tow volumes in an unlike manner. Graphically, this is observed as nonparallel lines of delay between service disciplines and can be seen in Figure 4-1. The interaction between pleasure craft volumes and tow volumes in Experiment II is also

²See also Chapter II above.

TABLE 4.4. ANALYSIS OF VARIANCE SUMMARY TABLES

Experiment I

Source	Sum of Squares	DF	Mean Squares	F Ratio	Probability
A Volume	2,257,515	3	752,505	145.1	0.0
B Service Disciplines	99,879	3	33,293	6.4	0.0
AB	193,825	9	21,536	4.1	0.0
Error	3,338,638	644	5,184		

Experiment II

Source	Sum of Squares	DF	Mean Squares	F Ratio	Probability
A Volume	1,407,298	3	469,099	95.442	0.0
B Pleasure Craft Vol.	165,046	2	82,523	16.790	0.0
AB	61,709	6	10,285	2.093	.10 > .05
Error	2,374,027	483	4,915		

Experiment III

Source	Sum of Squares	DF	Mean Squares	F Ratio	Probability
A Volume	492,587.01	3	164,195.67	61.274	0.0
B Separation	85.56	1	85.56	.032	.10 < .90
AB	235.21	3	78.40	.029	> .990 < .995
Error	862,860.02	322	2,679.69		

significant at the 10% level, which is shown by nonparallel lines in both Figures 4-2 and 4-3.

Conclusions

What can be said from the above model testing? Primarily that the LOKSIM model performed its simulation function extremely well. The additional queuing disciplines operated practically faultlessly within the set of 28 simulation runs. The breadth of the testing which the simulator has undergone suggests that very few, if any, logic errors exist in the LOKSIM program. More rigorous testing may uncover a few, but it is unlikely that they will be anything but very minor ones.

Some specific observations of the model testing are summarized as follows:

- (1) The way in which tows are processed, the service disciplines, indeed does have a significant effect on tow delays at high volumes. The most startling effect is the high average delay per tow tabulated for the system operating under the first-come-first-serve rule. The difference of about 100 minutes in average delay at the highest volume level casts great doubt upon the results obtained through using the WATSIM model [5] at high utilization levels. The FIFO rule as incorporated in the WATSIM simulator overstates delays by 100% at a utilization rate of 92% in the large chamber and 71% in the small one. This means that WATSIM output should be analyzed extremely carefully at high utilization levels to prevent improper conclusions. At low and medium utilizations it makes very little difference how the lock is operated. For utilization rates of 22%/17% and 48%/35%, there is no real practical difference between all four mean delay

values. At the third level, 76%/52%, the FIFO rule produces noticeably greater delays but there is only a difference of 18 to 20 minutes. The three other more practical operating rules remain bunched together.

- (2) Pleasure craft do cause considerable delays to commercial tows under the logical assumptions of the LOKSIM model. The effect becomes more pronounced, of course, as the tow volume increases; but at lower volumes many pleasure craft can be processed at little expense to tow delay. At the 19.20 tows per day level, for example, an additional 50 pleasure craft per day only raised the ADPT by about 22 minutes. An additional 9 tows per day would have increased the ADPT by 26 minutes if no pleasure craft were present. The significant differences do suggest that improved methods of simulating pleasure craft operation should be developed. Much of the logic used in the LOKSIM model in its handling of pleasure craft has no empirical basis whatsoever. Field data collection is required to formulate more realistic simulation techniques. After the model has been suitably refined, different service techniques could be developed for testing with the model.
- (3) Chamber separation has no significant effect upon average tow delay at the lock simulated. This conclusion may not be generalizable across all inland waterway locks. Special channel conditions may produce large differences between long and short entry times, and in these cases separated chambers may be attractive and justifiable. These special cases can be simulated, and localized conclusions drawn.

V. A STATISTICAL BARGE TOW SPEED FUNCTION

The tow speed function currently used in the inland waterway simulation program, WATSIM [5], has several shortcomings. The first of these is its unknown reliability for accurately predicting the speeds of tows with high horsepower. A second drawback is the complexity of the function. This chapter summarizes the development of a simpler, yet accurate, equation for computing tow speeds in WATSIM. A complete description of the study is available in a separate technical memorandum [24].

The Howe Speed Function

1. Development of the Function

The speed function currently used in WATSIM was developed in the early 1960's by Charles Howe [25, 26, 27], primarily to assist in equipment selection for waterway operations. The equation's parameters were estimated using data from actual tow movements, towboat log books, and prototype tests. The resulting equation was of a log-linear form, as this was consistent with what was known about marine speed functions.

Howe developed his equation by formulating expressions for the resistance of the tow and the effective push of the towboat, both of which were quadratic functions of tow speed. He then equated these two expressions and solved for the equilibrium tow speed. The resulting tow speed function can be represented (in a computational format) by the following equations:

$$R = 0.07289 e^{1.46/(D-H)} H^{0.6+50/(W-B)} L^{0.38} B^{1.19} + 172 \quad 5-1$$

$$R_s = 0.00086 V_D^{2-4/3} [(52 + 0.44H) HLB + 24300 + 350Hp - 0.0206Hp^2] \quad 5-2$$

$$S_1 = \frac{-1.14H_p + \{1.3H_p^2 - 4R [(-1)^{d+1}R_s - 31.82H_p + 0.0039H_p^2 - 0.38H_pD]\}^{0.5}}{2R} \quad 5-3$$

$$S = S_1 + (-1)^{d+1}V \quad 5-4$$

where

D = channel depth (feet)

H = average flotilla draft (feet)

W = width of the channel (feet)

B = flotilla width (feet)

L = flotilla length (feet)

H_p = towboat horsepower

V = current speed (mph)

d = 0 for upstream travel, 1 for downstream travel

e = base of the natural logarithms

S = equilibrium tow speed (mph)

Variable R is related directly to the resistance function, while R_s is a slope drag factor. S₁ is the computed still water tow speed, which is subsequently adjusted for account for current speed.

Comparison of predicted versus actual tow speeds revealed that the function had a positive bias. Hence, Howe derived correction equations by means of simple linear regression for various waterways, as follows:

$$\text{Ohio River:} \quad S_a = 1.77 + 0.525S \quad 5-5$$

$$\text{Mississippi River:} \quad S_a = 1.86 + 0.75S \quad 5-6$$

$$\text{Illinois Waterway:} \quad S_a = 3.10 + 0.56S \quad 5-7$$

where S_a is the adjusted tow speed.

2. Modification for Use in WATSIM

The Howe equation was admittedly invalid for towboats with horsepower ratings of 4000 or more, as the predicted speed decreases with increasing horsepower. To rectify this situation, tow speed was plotted against horsepower on semi-log paper; and the resulting curve simply extended into the higher horsepower ranges. The following modified form of 5-3 was then derived:

$$Sl = \frac{-1.14Hp + \{XHp^2 - 4R [(-1)^{d+1}R_s - YHp + XHp^2 - YHpD]\}^{0.5}}{2R} \quad 5-8$$

where

$$X = 1.252 \times 10^{-4}$$

$$Y = 1.446$$

Use of 5-8 instead of 5-3 for towboats with more than 3200 horsepower allows speed to increase with horsepower up to about 5000-6000 hp, where the calibrated speeds begin to taper off. The effect of this correction is illustrated in Figure 5-1.

The only other modification introduced for simulation purposes was to impose a minimum speed of 1.0 mph.

3. Critique of the Howe Function

The question has arisen whether or not the Howe speed function provides accurate results over the range of flotilla characteristics and channel characteristics which are encountered in simulation applications. The inapplicability of the function for tows with high horsepower ratings was reduced via the modification described above. However, the accuracy of this correction procedure is unknown.

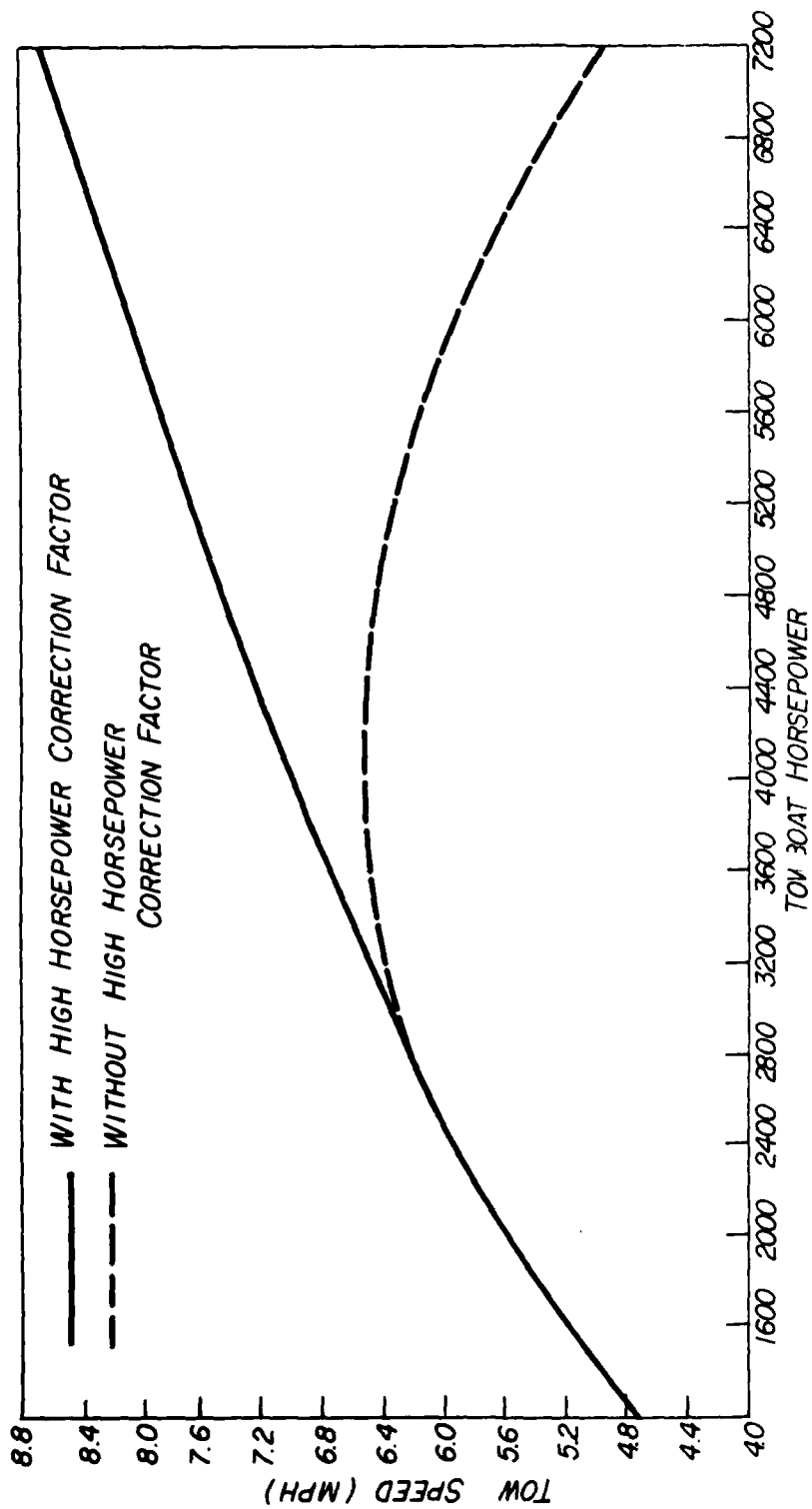


Figure 5-1 The Howe Speed Function With and Without the High Horsepower Correction

The function's complexity, which has been amply demonstrated, makes it virtually unusable for hand calculations. It was hoped that a simpler equation could be developed so that simple parametric inquiries regarding tow speeds could be made without the aid of the computer.

The Howe speed function is not so good a predictor of reality as its complexity might indicate. It makes many assumptions by failing to include factors which do have an effect on tow speed, such as whether the tow is integrated, nonintegrated or semi-integrated, and whether the drafts of the barges are consistent or varied, and how they vary.

These criticisms are not meant to imply that Howe's path-breaking analysis is incorrect. His function is probably quite good for predicting the speed that a tow is capable of attaining, which may well be the most appropriate consideration for equipment selection purposes. For simulation purposes, however, what is needed is a relatively simple function which predicts the speeds actually attained by tows under a variety of conditions.

Methodology

The statistical technique of multiple linear regression analysis was used in this study to develop several tow speed functions with the desirable properties specified above. The work of Howe formed a very important study input, as he indicated what variables were important in determining tow speeds and what types of variable interactions were likely to be significant.

Obtaining a large data set with simultaneous observations on all the variables of interest is usually a major obstruction to building a valid regression model. In this study, however, no real difficulties of this type were encountered. The Corps of Engineers had collected continuous locking operations data at all locks on the Ohio River and its tributaries

during the period December 1970 to January 1971, and these data were made available to PTTSC. For each lockage observed during the two-month period, the following values (among others) were recorded:

- (1) Vessel identification number
- (2) Horsepower of the towboat
- (3) Day of the month of the observation
- (4) Direction of travel of the tow
- (5) Arrival time at the lock approach point
- (6) Departure time from the lock clearance point
- (7) Total number of loaded barges
- (8) Total number of empty barges
- (9) Tow length in feet
- (10) Tow width in feet
- (11) Maximum tow draft in feet
- (12) Lock I.D. number

The first item above is particularly important, for it makes possible identification of consecutive observations of the same towboat at different locks in the system. Since the data were arranged sequentially by lock, and then chronologically for each lock, it was relatively straightforward to scan the data for two adjacent locks and identify individual tow trips between them. A computer program, named CONVERT, was written to accomplish this scan and produce the requisite regression input data. The operation of this program, which is diagrammed in Figure 5-2, proceeded as described below.

All tows at the first lock of a chosen pair were read into arrays. Each tow at the second lock was then compared against this array to see if the same tow appeared at both locks during the period. If a match of

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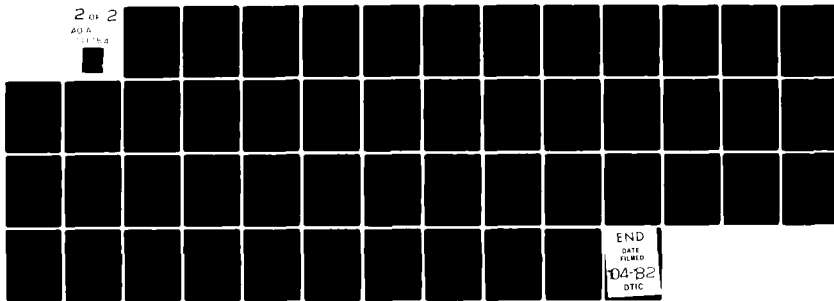
PENNSYLVANIA TRANSPORTATION AND TRAFFIC SAFETY CENTER--ETC F/6 9/2
ANALYSIS OF WATERWAY SYSTEMS.(U)

SEP 72 J L CARROLL, M S BRONZINI, J C HAYWARD DACW23-72-C-0009
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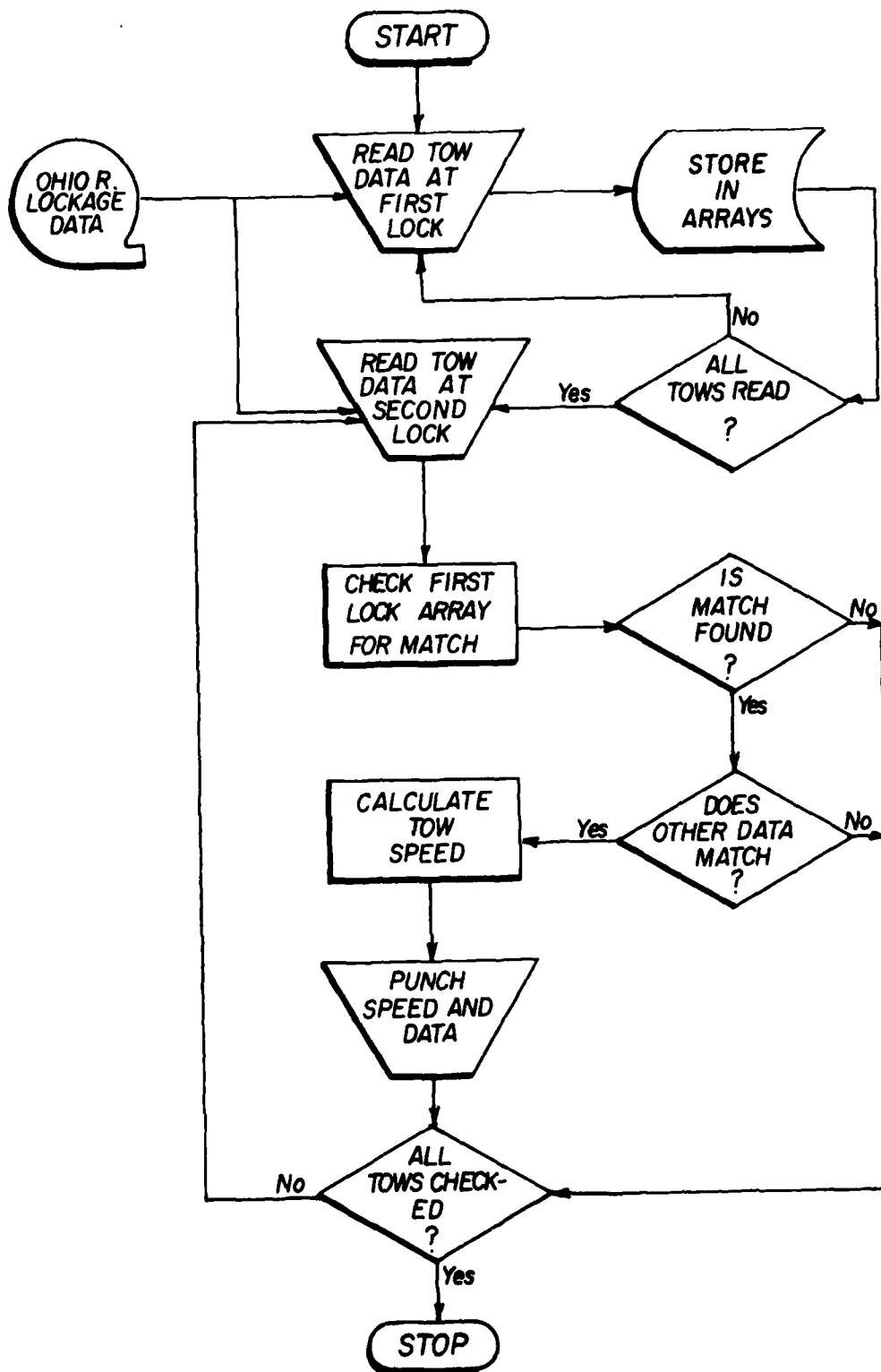


Figure 5-2 Macro Flow Diagram of CONVERT

towboats was found, other characteristics (in addition to the vessel I.D. number) of the matching pair were checked. These include the number of empty and loaded barges, the flotilla dimensions, and the direction of travel. If these checks were satisfied, the transit time was calculated as the difference between the times when the tow left one lock and arrived at the other, and then converted into travel speed. This value was then checked to insure that the speed was greater than the current speed if the tow was moving downstream, or greater than one mile per hour for tows moving upstream. If these checks were satisfied, the observed speed, the flotilla characteristics, and the channel characteristics were punched onto a data card.

This program was used to produce a deck of 703 observations for use in developing a speed equation. An additional 175 observations were later obtained to serve as an independent data set for further testing of regression equations.

Various transformations of the data described above were performed to obtain additional independent variables for regression purposes. These included sums and differences, cross products, and logarithms.

Potential speed equations were selected by means of a stepwise regression procedure [28, p. 171]. Both linear and log-linear functional forms were experimented with. Computer programs included in the Penn State Computation Center's statistical package [29, 30] were used for all calculations.

Results

1. Linear Equations

Seven statistical tow speed functions developed via the methods outlined above are displayed in Table 5.1. The initial regression run simply used the basic variables (i.e., no transformed variables were used) and produced the Linear 1 equation, with a surprisingly high fraction of explained variance, R^2 , of 0.76. Encouraged by this result, the variable H_{p1} , square root of horsepower, was added, as this is more consistent with normal speed versus power relationships than a linear term; and signed current speed (plus for downstream travel, minus for upstream) was introduced. The resulting equation, Linear 2, had a lower R^2 (≈ 0.74), but did not have any coefficients with the wrong sign, i.e., with a sign opposite that expected intuitively.¹

At this point the complete set of transformed data was introduced into the analysis, resulting in the Linear 3 equation with $R^2 = 0.76$. The equation shown in Table 5.1 was that for the 11th step of the run. The computer run actually terminated at step 28, when the equation contained 20 variables and had an R^2 of 0.79. However, many of these extra variables had seemingly incorrect signs, so the Linear 3 equation was chosen as being more reasonable, at the expense of only a 3% reduction in R^2 .

Reviewing the Linear 3 results, it was suspected that outliers were having an inordinately large effect on the predictive ability of the equation. Accordingly, the data set was edited to remove a small number ($< 1\%$) of observations which were judged to be erroneous or unreasonable,

¹In Linear 1, V has a negative coefficient. The negative coefficient on H_p in Linear 2 is cancelled by the much larger positive coefficient on H_{p1} .

TABLE 5.1. EQUATIONS DEVELOPED BY REGRESSION

Equation Name	Equation
Linear 1	$Sp = 10.428 - 5.39A + 0.00104Hp - 0.02W - 0.102D - 0.193B1 - 0.0589Be - 0.0393V + 0.839C; R^2 = 0.76.$
Linear 2	$Sp = 6.256 + 0.173 Hp1 - 0.00131L - 0.0208W - 0.174B1 + 0.000363R + 0.244C1 - 3.565A - 0.000557Hp; R^2 = 0.74.$
Linear 3	$Sp = 7.115 + 0.116Hp1 - 0.164B1 + 0.227C1 - 3.807A - 0.000402L(Be) + 0.00147W(Be) - 0.000282W(Bt) + 0.000037(D(R-W)) + 0.0222(Be)(Bt); R^2 = 0.76.$
Linear 4	$Sp = 7.652 - 4.567A + 0.1032Hp1 - 0.1781B1 + 0.2496Be + 0.1078C1 - 0.000427L(Be) + 0.0000377(D(R-W)) + 0.0236(Be)(Bt) - 0.000273W(Pb1) - 0.00388W(Be) + 0.00000766LW; R^2 = 0.83.$
Linear 5	$Sp = 7.348 - 3.93A + 0.0915Hp1 - 0.04288ERU + 0.1475C1; R^2 = 0.75.$
Logarithmic 1	$Sp = 10^{0.13} A2^{0.285} Hp^{0.314} D^{0.123} (Be + 1)^{0.076} R^{0.123} (V - D)^{0.552} (Bt + 2)^{-0.268} V^{-0.808} W^{-0.133}; R^2 = 0.80.*$
Logarithmic 2	$Sp = 10^{0.0358} A2^{0.3355} Hp^{0.3076} D^{0.1113} (Be + 1)^{0.07437} R^{0.1187} (V - D)^{0.4888} C^{0.0489} (Bt + 2)^{-0.2788} V^{-0.7003} W^{-0.1046}; R^2 = 0.82.*$
<p>A = Directional variable (0 = down, 1 = up)</p> <p>A2 = Directional variable (1 = up, 10 = down)</p> <p>Be = Number of empty barges</p> <p>B1 = Number of loaded barges</p> <p>Bt = Total number of barges</p> <p>C = Current speed (mph)</p> <p>C1 = Directional current speed (mph) (+ = down, - = up)</p> <p>D = Maximum flotilla draft (ft.)</p> <p>Hp = Towboat horsepower</p> <p>Hp1 = Square root of horsepower</p> <p>L = Flotilla length (ft.)</p> <p>R = Channel width (ft.)</p> <p>Pb1 = Percentage of barges loaded</p> <p>V = Channel depth (ft.)</p> <p>W = Flotilla width (ft.)</p> <p>Sp = Tow speed (mph)</p> <p>ERU = $5.67B1 + Be$</p>	

*R² computed on the basis of logarithmic deviations.

and the stepwise regression run was repeated. This produced the Linear 4 equation, with an R^2 of 0.83. Here, however, the coefficients for variables Be, Be x Bt, and L x W seem to have incorrect signs.

2. Log-Linear Equations

To determine if an exponential functional form would produce a better fit to the data, two additional runs were made, using the unedited and edited data decks but with logarithmic transforms of the variables. The resulting equations, respectively, are designated as Logarithmic 1 and Logarithmic 2 in Table 5.1. Both of these explain in excess of 80% of the variance in \log_{10} of tow speed, but have incorrect signs for the exponents of flotilla draft, empty barges, and channel depth.

3. The Linear 5 Equation

Analysis of the results thus far obtained revealed that the three most important factors for predicting tow speeds were: (1) the direction of travel; (2) the number of loaded barges in the flotilla; and (3) towboat horsepower. These three variables collectively explained over 70% of the variance in tow speeds for all regression runs. All other variables seemed to be functioning as adjustment factors, which perhaps accounts for some of the unexpected reversals in the signs of the regression coefficients. Specific adjustments at work in various equations appeared to be based upon the relative proportions of loaded and empty barges, and selected channel characteristics.

In view of the above observations, the following functional form for a simplified speed equation was hypothesized:

$$Sp = \alpha_0 + \alpha_1 A + \alpha_2 Hp1 + \alpha_3 ERU + \alpha_4 Cl + \alpha_5 (V-D) + \alpha_6 \frac{RV - WD}{RV} \quad 5-9$$

where all variables are as defined in Table 5.1. Variable ERU (Effective Resistance Units), defined as a weighted sum of loaded and empty barges, is a surrogate measure of the mass which must be moved by the towboat. The weighting factor of 5.67 for loaded barges was derived as the ratio of loaded draft to empty draft, assumed to be a 8.5 feet and 1.5 feet, respectively. The last variable in 5-9 expresses the approximate cross-sectional area of the prism of water surrounding the towboat as a fraction of the total river cross section. Hence, as this variable decreases, some of the restricted channel effects noted by Howe should come into play, and tow speed should decrease.

The initial regression run for this equation showed that there were not enough observations on small-dimensioned channels to make the final variable in 5-9 significantly different from unity, so this variable was deleted. The subsequent stepwise regression produced the Linear 5 equation in Table 5.1, with an R^2 value of 0.75. It should be noted that all coefficients in this equation have the expected sign, but that the depth minus draft variable, $V - D$, was not entered into the equation. Hence, average current speed, signed by direction of travel, is the only channel characteristic to which tow speed is sensitive in this equation.

4. Further Tests

Following Howe's technique, linear bias correction equations for the two logarithmic equations were developed by regressing actual tow speeds against predicted speeds. For comparative purposes, similar results were obtained for the Howe speed function, both with and without the Ohio River correction factor. The results of these tests were as follows:

$$S_a = 2.090 + 0.336 \text{ (Logarithmic 1)} \\ (0.176) (0.015) \quad R^2 = 0.69$$

$$S_a = 1.734 + 0.746 \text{ (Logarithmic 2)} \\ (0.146) \text{ (0.017)} \quad R^2 = 0.78$$

$$S_a = 1.398 + 0.528 \text{ (Howe)} \\ (0.300) \text{ (0.021)} \quad R^2 = 0.46$$

$$S_a = -0.401 + 1.017 \text{ (Adjusted Howe)} \\ (0.370) \text{ (0.041)} \quad R^2 = 0.46$$

The R^2 values for the logarithmic equations provide a meaningful basis for comparing these with the linear equations and show that the adjusted log equations are acceptable from a predictive power standpoint. It is also noteworthy that the correction equation for the Howe speed function is statistically equivalent to that reported by Howe, and the R^2 value of 0.46 given above corresponds closely to the value achieved by Howe ($R^2 = 0.48$) with his Ohio River data. These results tend to indicate that both Howe's tests and the present study used data from the same population.

As a final test, all equations developed in this study and the two Howe equations were applied to the independent data set of 175 observations obtained from the Ohio River lockage data, as described previously. The resulting tow speed predictions were compared with the actual speeds, using the simple linear regression model demonstrated above. The results of this test confirmed those already presented, i.e., comparable R^2 values and bias corrections² were obtained in all cases.

Conclusions and Recommendations

All of the regression equations displayed in Table 5.1 are acceptable for predicting tow speeds, and all are more accurate than the Howe function.

²As would be expected if the models are correct, no significant bias corrections were observed for the five linear equations.

This conclusion is supported primarily by the significantly higher R^2 values obtained with these equations, as opposed to those achievable with the Howe function. Further, even the most complex of the regression equations is markedly simpler than Howe's formulation. Hence, the two criteria of accuracy and simplicity both favor substituting a regression equation for the Howe speed function in WATSIM.

Among the seven equations, which one to use is not quite so clear. The choice can be narrowed readily to Linear 2, Linear 4, Linear 5, and Logarithmic 2, based upon the considerations entering the development of the respective equations. Beyond this, however, the final choice is a matter of preference and judgment. The authors tend to favor one of the linear functions, as they are computationally simpler and do not require subsequent application of a bias correction.

Forced to choose one equation, the authors would recommend the use of Linear 5. This is the simplest of all the equations, while at the same time it incorporates certain theoretical considerations in the variables used. It also appears to be capable of expansion and modification in the future if desired. Complete regression results for this equation are as follows:

$$Sp = 7.348 - 3.93A + 0.0915(Hp^{0.5}) - 0.0429(5.67Bl + Be) + 0.1475[(-1)^A C]$$

$$(1.652) \quad (0.43) \quad (0.0057) \quad (0.0022) \quad (0.0636)$$

$$R^2 = 0.75; \quad n = 710; \quad F = 533$$

where

Sp = tow speed, mph

A = 0 for downstream travel, 1 for upstream travel

Hp = towboat horsepower

Bl = number of loaded barges

Be = number of empty barges

C = average current speed, mph.

The equations developed in this study are strictly applicable only to the Ohio River, or to waterways exhibiting a similar array of channel and fleet characteristics. Additional work and data for other systems will be required to test the validity of these equations for other waterways, or to develop a universally applicable statistical tow speed function. The lockage data for the Ohio River's major tributaries would provide a good starting point for such further studies.

In connection with the above, perhaps the most valuable contribution of the present study is not the specific speed equations, but rather the screening service which has been performed. The most significant independent variables have been identified, and the linear functional form has been found to be adequate. Hence, for future regression studies, one could start with the variables in the Linear 5 equation and add others as needed.

Finally, it should be noted that the major shortcoming of the speed functions developed in this study is their insensitivity to channel characteristics other than current speed. Howe's work has shown that channel restrictions can significantly affect tow speeds, but none of the regression equations admit such effects. This is more a function of the data base than anything else, since no observations on tow movements through restricted channels were available. Additional data will be needed to correct this deficiency. If such data are collected, the channel variables included in 5-9, or some transformations of them, would probably suffice for initial experimentation purposes.

VI. METHODOLOGICAL DESIGN FOR WATERWAY SYSTEMS PLANNING

Previous chapters have described research on improving the waterway simulation process and have given the results of specific simulation experiments. The present chapter presents the findings of the initial phase of a relatively long-term project devoted to the development of a set of models and analytical tools suitable for the planning of navigation improvements on a systems basis. Study efforts were focused upon reviewing previous transportation system models, deriving a conceptual formulation of the overall systems analysis methodology, and surveying demand forecasting and modal split techniques.

Background and Objectives

The Corps of Engineers has recognized for some time the need for performing systematic analyses of the operation of the inland navigation system and for evaluating new or replacement projects in a systems framework. A manifestation of this concern was the formation of a Task Force by the Chief of Engineers in July of 1970, charged with articulating and detailing a method for applying systems analysis to the inland waterways. The Task Force report [31] was completed early in 1971 and had as a recurring theme the need to develop waterway transport demand models which could be used in conjunction with the Corps' waterway simulation capability in the context of an equilibrium analysis. It was in support of these generalized Task Force recommendations that the present study was undertaken. The primary objective of the work was to determine what specific demand forecasting techniques appeared to be amenable to immediate implementation as parts of an integrated waterway systems analysis. As a necessary adjunct, the components and interrelationships of the overall equilibrium analysis methodology were also formulated.

Waterway Systems Planning and Analysis

Prior to presenting the proposed methodological framework, it is necessary to consider briefly exactly what this analytical tool is intended to accomplish. Other authors have expounded at length on the intents and purposes of transportation systems planning, and their arguments need not be repeated here. Particularly cogent expositions on the subject have been provided by Manheim [32], Thomas and Schofer [33], and others [34, 35]. Also, an appendix [36] to the Task Force report lucidly summarizes transportation modeling techniques and their application to the inland waterways.

The authors cited above are in general agreement that the transportation planning process consists of the following steps:

- (1) generation of a set of alternatives (plans, designs, operating policies, etc.) sufficiently attractive to be worthy of detailed testing and examination;
- (2) prediction of the impacts of implementing each alternative;
- (3) selection of an alternative based upon an evaluation of the impacts.

Impact prediction, the second of the above steps, is the subject matter of what is commonly referred to as "transportation systems analysis." Given the attributes of a proposed alternative, it is the job of an impact prediction methodology or procedure to estimate the consequent values of the decision variables to be used in the selection stage of the planning process.

Manheim [32] has succinctly summarized the impact prediction problem to be one of determining equilibrium flows in transport networks. "Equilibrium" here refers to the fact that transport service characteristics are

a function of flow volumes, while simultaneously, flow volumes are partially determined by service characteristics (price, transit time, terminal congestion, etc.). It is precisely this equilibrium flow prediction problem that is addressed by the waterway systems analysis methodology presented herein.

Finally, the models described below are intended for use in a planning context. That is, analyses of long range structural or significant operational modifications of a waterway system are contemplated. Of course, the same methodology could be used to analyze short-term operational improvements with very little change. However, in the short run the demand/supply equilibrium point is virtually fixed, so a somewhat simplified analytical procedure (e.g., a single-lock simulation) could be employed to advantage.¹

Proposed Methodology

Figure 6-1 is a simplified diagram of the process which might be used to analyze prospective waterway improvements within a systems context. The analysis begins with an estimate of the total demand for origin-destination (O-D) transport of commodities which are susceptible to movement by water. This total demand is input to a modal split model which apportions the traffic among the competing modes on the basis of estimated transport costs and quality of service. The performance of each mode in serving its portion of the demand is then estimated. These actual modal performance values are subsequently compared with the corresponding values used to compute the traffic split. If significant discrepancies exist, a new modal allocation is made resulting in revised transport demands upon each mode.

¹Antle et al. [36] treat the long-run vs. short-run question in detail.

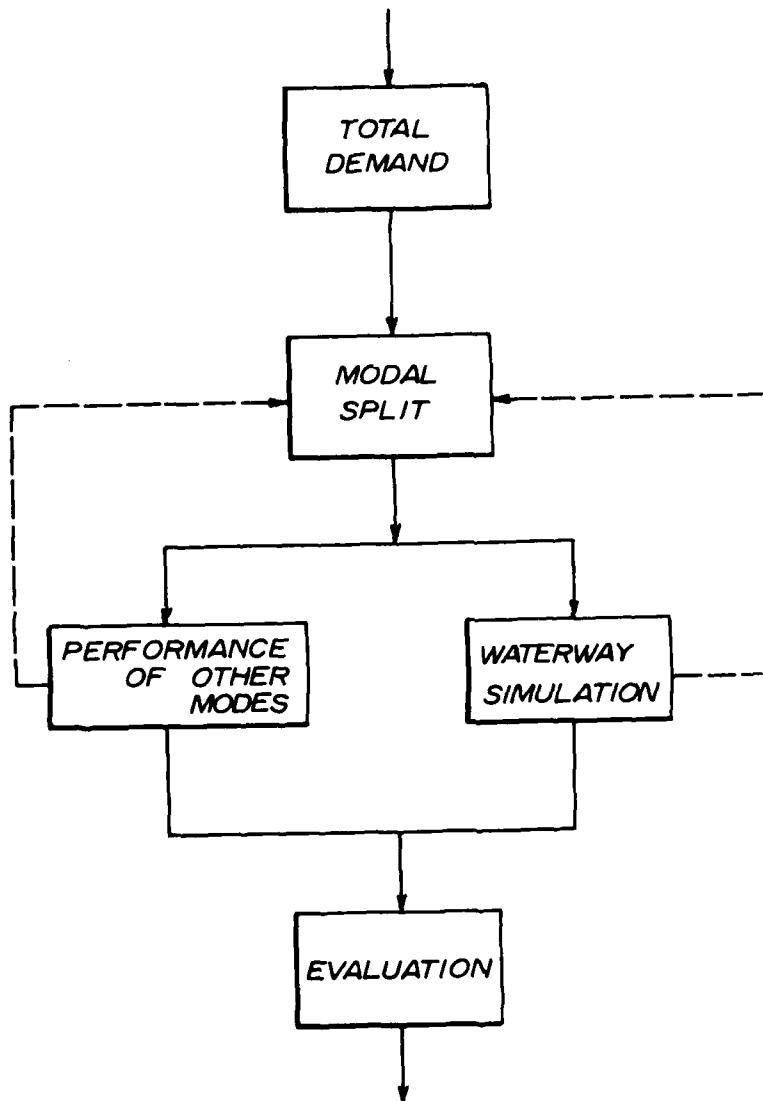


Figure 6-1 Methodology for Waterway Systems Analysis

This cyclic process is continued until supply-demand equilibrium is achieved for each mode.

It is the feedback of O-D delay or transit time values from the simulation models to the modal split model which provides the equilibrium flow prediction capability mentioned previously. Conceptually, this looping process is nothing more than an iterative or trial-and-error approach to estimating simultaneously the flow and transport service values which characterize a point of market stability. Altering either the total demand or the waterway system (or some other mode) will disturb this equilibrium position; the framework depicted in Figure 6-1 provides a mechanism for determining where the new equilibrium point will lie.

The demand forecasting and modal split elements of the proposed methodology are discussed further below. Waterway simulation and evaluation have been treated in previous reports to the Corps [1, 37]. Investigation of performance versus flow models for other modes was beyond the scope of this study. It should be noted, however, that the development of such models at the same level of detail as the waterway simulation model clearly should not be attempted by the Corps of Engineers. Rather, the Corps will have to rely upon other governmental agencies (most likely the Department of Transportation) for inputs to this portion of the methodology.

Forecasting Commodity Flows

The job of a commodity flow forecasting model is to determine the O-D movements of all commodities which are now or might potentially be shipped on the waterways. Research has been completed on further defining the forecasting task, reviewing present COE forecasting methods, and surveying some basic approaches to forecasting.

1. The Forecasting Task

Prior to selecting a particular forecasting technique, it is essential to state clearly the desirable or required characteristics of the forecasting model. The following specifications for a "second-generation" COE commodity flow forecasting model are suggested:

- (a) The model must be operational and easy to use;
- (b) Forecasts must be long term (up to 50 years);
- (c) The forecasts must be easily updated;
- (d) Model maintenance must be minimal;
- (e) Computational time must be reasonable;
- (f) Model output must be in the form required for input to a modal split model.

Needless to say, accuracy and reproducibility of the forecasts are of paramount importance.

Another important initial step in building a forecasting model is defining the geographical area to be covered by the model and the individual commodities to be included in the forecasts. It will probably be most advantageous and efficient for the Corps to develop national commodity flow forecasts for input to all COE navigation system studies, rather than developing subregional forecasts. Commodity flows between major ports should be identified in as detailed a fashion as possible. Further, all potentially waterborne commodities must be included, not only bulk commodities. The rising prominence of LASH/SeaBee shipments on the inland waterways underscores the importance of this observation.

The preceding paragraphs have indicated that O-D flows are the variables to be estimated. It is equally plausible to forecast demand and supply for each commodity at each port, then use a distribution model

(gravity model, transportation model, etc.) to allocate supplies to demands, thereby deriving commodity flows. In fact, this technique is used in urban transportation planning and has been used in some regional transportation studies (e.g., [35], vol. 2). The present study concentrated on flow forecasting, primarily because time did not permit a comprehensive review of distribution models. However, the techniques to be discussed below are also applicable to demand/supply forecasting.

2. Present COE Forecasting Methods

The Corps of Engineers currently makes O-D flow projections² for ten aggregated commodity groupings, as follows: (1) selected grains; (2) bituminous coal; (3) petroleum and petroleum products; (4) cement, stone, sand, and gravel (CSSG); (5) sulphur; (6) iron ore and iron and steel products (I&S); (7) industrial chemicals; (8) agricultural chemicals; (9) other selected commodities; and (10) miscellaneous commodities. Forecasts are made for each decade of what is commonly a 50-year study period.

A critical assumption implicit in Corps forecasts is that commodities presently (or historically) moving on the waterways will continue to do so, while cargo not presently shipped by water will not enter the system in significant quantities in the future. Additional assumptions and methods used for certain commodities are encapsulated below.

Grain. The Corps assumes that the percentage of total grain traffic moving on the waterways will remain constant; hence, analysis is directed toward forecasting total grain movements. This is accomplished by studying projected yield and acreage indices provided by the Department of

²Information presented here was derived from several published Corps reports [38, 39, 40], and from conversations with COE representatives.

Agriculture, and by analyzing projections of domestic consumption and grain exports.

Coal. Projections here are exceedingly difficult due to the impact of technological change and shifting societal priorities. The Corps relies upon interviews with major suppliers and users, and upon indices of energy requirements to prepare the required forecasts. Final projections are in large measure a matter of judgment on the part of Corps experts.

Petroleum. The "petroleum per capita index" is the major input for these forecasts, as well as interviews with suppliers and users. Judgment is also a key factor here.

Cement, Stone, Sand, and Gravel. Since these commodities are used primarily in the building and construction trades, shipment forecasts are related to the construction index for each major urban area.

Iron and Steel. Preparing accurate forecasts for this group is most difficult, due in part to competition from other modes for the movement of high-valued semi-finished products. International trade is also an important factor.

Agricultural Chemicals. The Department of Agriculture provides the Corps with projections of future needs for chemical fertilizer based on their own estimates of crop acreage. Since fertilizer plants tend to locate in their market areas, the requisite flows of chemicals can be derived.

Other and Miscellaneous. These movements are simply forecasted as a constant percentage of the total flow.

In summary, the Corps generates forecasts of future commodity flows using judgment based on interviews with major suppliers and consumers, an analysis of pertinent economic indices, and a review of historical data.

Trend analyses, when done, are carried out at the least sophisticated level. The bias inherent in relying upon interviews with shippers is virtually immeasurable. Any practical application of statistical or other quantitative techniques to augment the Corps' subjective judgment would likely yield more reliable forecasts. A need for technological forecasting is also indicated.

3. Some Basic Approaches to Forecasting

Forecasting techniques can be divided into two basic categories: structural and nonstructural forecasts. Structural forecasts are conveniently thought of as economic or statistical models designed to explain observed commodity flows. Statistical techniques are used to examine historical and/or cross-section commodity flow data as functions of various explanatory variables such as population, industrial activity, agricultural production, and so on. The resulting structural relationships can then be used as predictive tools if the future values of the explanatory variables can be independently derived.

Nonstructural forecasting also relies upon statistical analysis of historical data. Here, however, the primary explanatory variable is time, and underlying economic relationships can be considered only in a parametric fashion. Although the basic idea of nonstructural forecasting is the rather simple notion of trend analysis, some relatively sophisticated mathematical methods can be used in practice, including exponential smoothing and various nonlinear functional representations.

Both structural and nonstructural forecasts are based on the premise that the future state of technology and society will be much the same as that in the past. Recent events such as the increasing public awareness of environmental pollution, however, demonstrate that this is a somewhat

tenuous hypothesis. Hence, the art of technological forecasting is gaining support as a means of dealing with such uncertainties.

These three approaches to forecasting are treated in more detail below.

4. Structural Forecasts

Structural forecasting methods may be classified into three major categories: (1) single-equation regression models; (2) econometric models or multiple-equation regression models; and (3) input-output models.

Critiques of each of these methods are presented below.

Regression Models. Single-equation regression models [28] are formulated on the hypothesis that the value of some dependent variable (freight flow) is related to, or determined by, one or more independent variables (industrial production, GNP, time, etc.). In most practical applications, a linear relationship of the following form is assumed:

$$Y = a_0 + a_1X_1 + \dots + a_pX_p \quad 6-1$$

where

Y = dependent variable

X_1, \dots, X_p = explanatory variables

a_0, \dots, a_p = coefficients determined by least squares regression

It is often necessary to transform the variables and/or the equation in order to match the structure of 6-1. In the present context, Y would be the yearly flow in tons of a particular commodity between two ports, and the X 's would purport to measure the relevant characteristics of the shipping and receiving ports. Upon determining the parameter values by means of historical and/or cross-section data, a future Y value is found by inserting the future values of the X 's into the equation.

This last statement highlights one of the chief factors inhibiting the usefulness of this method: future values of the explanatory variables may be highly uncertain, or they may be outside of the ranges covered by the data used to derive the parameter estimates. Additional practical problems, such as the need to select proper independent variables and the difficulties in obtaining a consistent data set, are covered in detail in any standard text on regression analysis [28]. There are also many statistical difficulties to be overcome, including multicollinearity, spurious association, and autocorrelation.

Econometric Models. An econometric model is essentially a system of simultaneous equations which dynamically represents the economic structure of a country or region [41, 42]. This system may be comprised of a few or several hundred functions; and thus, there is an obvious trade-off between model sophistication and computational tractability. The individual equations are of the form of 6-1, and parameter estimates are derived by regression analysis. Hence, the remarks in the preceding section apply here as well.

The major advantage of an econometric model lies in its dynamic nature. The dependent variable of one equation may be an independent variable in another. This interrelationship of equations more truly represents the structure of an economy. The high level of economic expertise and the quantity and quality of data required to build an econometric model are its major disadvantages. In addition, in the present context many of the structural relations which must be included in the model may depend upon flow variables for commodities whose movements are not being forecasted, thus greatly increasing the scope of the model's data requirements. This situation would likely inhibit the development and application

of such a model by the Corps of Engineers, although Corps support for an interagency effort along these lines is certainly warranted.

Input-Output Models. An input-output model [43, 44] treats an economic system as a universe of mutually interrelated sectors or industries. Each sector provides the others with some goods or service and, in turn, receives products and services from other sectors. The impact on other sectors of changing the input or output of one or more sectors can be studied with such a model. Input-output models are inherently descriptive and static, although they can be made dynamic with an attendant increase in complexity. Also, all interindustry relationships are assumed to be linear. An input-output model which is sensitive to transportation prices has been developed at The Pennsylvania State University [34], and the Department of Transportation is currently experimenting with input-output analysis [45].

Although input-output models are not in themselves forecasting devices, they can be used for this purpose if future model parameter values can be predicted. Typically, this requires knowledge of the exogenous demand for each sector's output or some notion of how interindustry technological coefficients are likely to change.

The major disadvantages of input-output analysis are similar to those of econometric models, i.e., an entire integrated economic structure must be modeled for the analysis to be meaningful. In addition, certain classes of generalized input-output models require specification of a linear objective function to be optimized, which introduces a further level of abstraction from reality into the analysis.

The Constancy Assumption. All structural forecasting methods have in common the assumption that model parameter values, determined from "calibration" or analysis of existing data, will remain constant throughout the study period. This assumption is probably valid in the short run, but its reliability is questionable from a long-term vantage. Of course, the constancy assumption is implicit in most planning efforts, so structural forecasting models cannot be rejected on this basis alone. Nonstructural forecasting methods attempt to dispose of this problem by dealing with the passage of time directly. However, as will be seen below, they do so by sacrificing a large measure of theoretical tenability.

5. Nonstructural Forecasts

Nonstructural forecasting typically utilizes trend analysis techniques to project the future according to what has occurred in the past. The only independent variable used is time, and other factors which may affect the dependent variables are ignored or are considered only indirectly. A second type of quantitative method which can be useful for preparing non-structural forecasts is what has come to be known as the "shift technique."

Trend Analysis. Trend analysis techniques [46] run the gamut of sophistication from simply visually fitting a trend line through data points to least squares, moving averages, and multiple exponential smoothing. The resulting quantitative description of a time trend can take on a variety of mathematical forms.

A simple moving average is representative of the general class of smoothing techniques and can be defined as follows:

$$M_t = M_{t-1} + \frac{X_t - X_{t-n}}{n}$$

6-2

where

M_t = moving average at time t

X_t = observation at time t

n = number of observations used to calculate the moving average.

Hence, the average of the most recent n observations is used to stabilize the trend estimate, and to provide a means of discounting the influence of observations in the distant past (i.e., prior to $t-n$).

Exponential smoothing can be most simply described as similar to a moving average with weights which decrease exponentially with the age of the data. The general equation for first degree exponential smoothing is as follows:

$$S_t = bX_t + (1-b) S_{t-1}, \quad 0 \leq b \leq 1 \quad 6-3$$

where

S_t = smoothed value at time t

X_t = observation at time t

b = smoothing constant.

As the value of b approaches unity, the most recent events exert more of an influence on the trend estimate.

Some technical problems in using smoothing methods include deriving an initial value (M_0 or S_0) and selecting a proper smoothing constant (n or b) for 6-2 or 6-3. Also, the availability of good historical data is crucial to the success of the method.

Multiple smoothing is simply a multistage application of the above methods, wherein the smoothed values from one stage are input as observations to the next stage. As another refinement, the random variation in the observations can be used to derive confidence limits for a trend line.

A recent example of the use of these techniques is a fairly sophisticated second degree exponential smoothing model constructed to forecast U.S. imports and exports [47].

The Shift Technique. A second way of looking at changes in a dependent variable over time is the so-called "shift technique" [48, 49, 50]. The fundamental hypothesis of this method is that the growth or decline of some regional economic activity is dependent upon two sets of factors: (1) those factors operating more or less uniformly over all observational units; and (2) those factors operating specifically within observational units. The shift technique is a simple method of sorting out the effects of these factors and comparing trends among different units.

The basic computations of the shift technique proceed as follows. Let X_{it} be the level of some economic activity (e.g., shipments of a commodity) at location i and time t , and let $X_{ot} = \sum_i X_{it}$. Then, the net shift at location i is calculated as

$$S_i = X_{it} - \frac{X_{ot} - X_o(t-n)}{X_o(t-n)} X_{i(t-n)} \quad 6-4$$

where changes in economic activity between times $t-n$ and time t are being analyzed. Thus, S_i measures the current difference between actual economic activity and that which would be expected if location i changed at the same rate as all locations collectively.

Interlocational shift comparisons are facilitated by computing the percentage of net shift:

$$P_i = 100 \frac{S_i}{\sum_i S_i} = -100 \frac{S_i}{-\sum_i S_i} \quad 6-5$$

Note that 6-5 guarantees that the sign of P_i will be the same as that of S_i ; and hence, P_i displays what portion of the total positive or negative shift accrues to a particular location.

If observations on the components of X_i are available, the shift analysis is easily extended in the "vertical" dimension to help in identifying the source of interlocational trend disparities. This process segregates the net shift S_i into a differential effect and a proportionality effect. The former measures the relative advantage which some locations enjoy with regard to certain components of X_i , while the latter examines the influence of the total study area's rapid or slow growth activities on S_i . Computational details are provided in the sources referenced above.

The shift technique is easy to understand and use, but it suffers from some serious limitations, most of which are due to the effects of aggregation. Other problems are discussed in detail by Houston [51]. Also, it is obvious that the shift technique is not in itself a forecasting tool, but it can be used by the analyst to provide some insight into the study area's differential growth patterns. As a further aid to forecasting, the shift could be used as the dependent variable in a regression model, thus providing a means of forecasting future shifts.

The Constancy Assumption Revisited. As aforementioned, nonstructural forecasting methods do not dispose of the constancy assumption, but merely cast it into a somewhat more restrictive form. Such methods assume that the trends established in the past will continue unaltered into the future, which is actually more untenable than the constant parameter assumption. Further, adoption of such a hypothesis removes the possibility of normative planning and, in fact, reduces the planning effort to the

level of merely reacting to immutable socioeconomic forces set into motion by preceding generations. Technological forecasting, which will be discussed next, has been promulgated as a means of escaping from the "constant future syndrome" which permeates much of present-day planning activities.

6. Technological Forecasting

As the time frame of forecasts is lengthened, the need to consider alternative techno-social futures, possibly differing radically from existing conditions, becomes important. The necessity for such analyses has been recognized by the military since the 1940's, and technological forecasting has recently come into use experimentally as a business management aid.

Technological forecasting might be defined as a systematic method of conceptualizing the course of future socioeconomic and scientific events in an industrialized society. A variegated array of means which supposedly accomplish this task have been proposed. Jantsch [52] has identified over 100 distinguishable versions of technological forecasting techniques, which he classifies into 20 different approaches in the following four major areas: (1) intuitive thinking; (2) exploratory techniques; (3) normative techniques; and (4) feedback techniques. A recent thesis by Rooney [53] presents a critique of technological forecasting methods. One intuitive technique, known as the "Delphi Method," appears to merit consideration for application to the commodity flow forecasting problem.

The Delphi Method. The Delphi Method [54, 55, 56] is essentially a descendent of the "brainstorming" session, wherein a group of experts gather to generate opinions about future events. Brainstorming, however, is likely to produce compromise rather than consensus, due to the

psychological effect of face-to-face confrontation of group members. This is avoided in the Delphi Method through the use of mailed questionnaires or some other cloistering mechanism.

Four rounds of questioning are generally used in the Delphi Method. Each expert first lists his opinions independently. An edited list of all ideas generated is then prepared, and the experts are asked to assign probabilities to their occurrence within different time frames. On the third round, composite probability distributions are returned to the experts, and those with responses outside the middle quartiles of the distribution are asked to either alter their views or provide some justification for them. On round four, a revised questionnaire with narrower time frames or probability ranges is remitted to the panel, along with the current consensus and the defenses of extreme views. If consensus does not occur after the fourth round, the process is simply repeated.

Many variations of the Delphi Method are in existence; the above is not a strict formulation, as there is none. The method avoids the impracticalities and problems of group discussion while achieving a true consensus. The major problems inherent in the method are the selection of experts and the formulation and revision of questionnaires.

Technological Forecasting and Commodity Flows. In summary, the Delphi Method or any other technological forecasting technique would not be a very practical means of preparing detailed commodity flow forecasts. However, it does appear that techniques of this genre could be profitably used to revise or modify flow forecasts resulting from a structural or nonstructural model.

7. Conclusions

There is no one best forecasting method, especially when the forecasting task calls for extra long projections. The method which considers all influencing factors--including technological change--and has the ability to predict turning points will usually generate the most accurate results and thus, in terms of output, will be the "best." In this respect, a properly constructed econometric model fills the requirement of a "best" method. On a national scale, an econometric model could be constructed to represent all transport services. It could provide a forecast of freight (and people) movements by each mode over each link in the national transportation network. Thus, both forecasting and modal split models would be synthesized.

Next on the list of "best" methods is a projection of all relevant intercity freight flows which could then be applied to a modal split model. The projection of freight flows between cities might be accomplished by a regression model or a nonstructural trend analysis model, depending on data availability and the level of sophistication deemed necessary.

Both these approaches require an enormous data bank, a high degree of economic and statistical expertise, and a significant amount of development time. Data requirements are severe, especially for the construction of an econometric model. The data must be valid, reliable, and historically consistent. In order to be successful, it is felt that these approaches must be applied on a national scale, so that all interregional flows and associated activities are considered. A federal agency with authority to gather data from all transport firms and associated entities should therefore be the developer and operator of such a model. In fact,

the Federal Department of Transportation is making the first major attempt in this direction with its national transportation input-output model.

Since the operational use of the above methods has not yet materialized, the Corps must continue to forecast inland waterway movements by either developing its own forecasting and modal split models or by continuing to use present methods. The development of sophisticated models would be extremely difficult for the Corps due mainly to data availability and manpower problems. Therefore, it is reasonable to assume that the Corps will continue to use present methods, at least for the short term. The immediate problem, then, is not the design of a new forecasting model, but rather how best to use existing techniques to improve present COE methods. With this in mind, the following should be considered.

The Corps has reliable and valid data on historical movements of commodities between ports. Exponential smoothing and extrapolation techniques could be applied to these data to yield at least a first estimate of future flows. The Delphi Method could then be applied, with the "panel of experts" comprised of representatives of major waterway users as well as experts in all related fields. This method would provide an insight into technological change and would also reduce the biases found in present industry interviews. With care, the Shift technique could be used to investigate growth patterns. The results of both the Delphi Method and the Shift analysis would then provide a basis for augmenting present judgments. The Corps could use this better judgment to adjust the projected trend line produced as a first estimate.

Additional details regarding the points raised above are provided in two papers by McLauchlan [57, 58]. Further specifications for a forecasting methodology are dependent upon the selection of a modal split procedure, which is discussed below.

Modal Split Techniques

The proposed waterway systems analysis methodology includes a modal split model to allocate O-D commodity flows among the transport modes competing for traffic in the area served by a waterway system. This model must be responsive to the level of service provided by each mode. This section presents a review of available freight modal split models, and develops a somewhat novel approach to freight modal split based upon diversion curve theory.

1. Existing Modal Split Models

Three existing modal split models, representing a substantial portion of the applicable research in this area, were reviewed: (1) the Silberberg model; (2) the Northwestern model; and (3) the Herendeen model. All three of the foregoing depend upon the use of statistical techniques for deriving modal allocation estimates.

The Silberberg Model. Silberberg [59, 60] developed a model for predicting regional coal movements on the Mississippi River system. This is a multiple linear regression model which predicts the supply of and demand for barge coal by region, as a function of economic activity and weighted average barge-versus-rail rate differentials. From these supply and demand estimates, O-D flows were developed using the linear programming transportation method.

Note that Silberberg was working with input and output at each port; hence, his model combines certain elements of both commodity flow forecasting and modal split. That is, use of this model would require the forecasting of only the economic activity variable used in the regression equation. Use of the linear programming distribution technique, however,

precludes application of the model to nonhomogeneous commodity groups [35, vol. 1, Appendix A].

Of immediate interest here is the modal split portion of Silberberg's model, which can be represented as follows:

$$Y_i = b_0 + b_1 I_i + b_2 R_i \quad 6-6$$

where

Y_i = supply of, or demand for, barge coal at port i

I_i = a measure of economic activity at port i

R_i = difference between weighted average rail and barge rates at port i .

For coal movements, Silberberg derived values for I from data supplied by the U.S. Bureau of Mines. Selection and measurement of this variable for other commodities could prove to be quite difficult. Collection of appropriate rate data presents another obstacle, although the Corps is presently required to use rate differences for project benefit calculations and, thus, may have the necessary information readily at hand.

Northwestern Model. The Northwestern model was developed at Northwestern University's Econometrics Research Center as one part of a broad-based study [61] of waterborne transportation demand and supply functions. The entire Northwestern study relied heavily upon microeconomic theory, and the freight modal split model is no exception.

The chief distinguishing feature of this model is the use of discriminant analysis for determining modal allocation for commodity groups which exhibit exclusive modal choice, i.e., homogeneous groupings. Discriminant analysis is kindred in spirit to regression analysis and makes use of a linear discriminant function to assign observations to populations so as

to minimize errors [12]. This technique was applied successfully to corn shipments in Illinois and to certain classes of international trade. The Northwestern researchers also concluded that heterogeneous commodity groupings were analyzed more appropriately via multiple regression techniques.

Since the original Northwestern Study, the Corps' Institute for Water Resources has applied the discriminant analysis model to the modal split of coal shipments in the Upper Ohio River Valley [62, 63]. The best function developed in the study, based on 51 coal movements (28 by barge, 23 by rail), was as follows:

$$\hat{Z} = -0.000053X_1 + 0.014388X_2 - 0.013872X_3 - 0.006522X_4 \quad 6-7$$

where

\hat{Z} = discriminant value

X_1 = time in hours for the movement

X_2 = average shipment size (tons x 10^{-5})

X_3 = rate of selected mode

X_4 = handling cost

and for which $R^2 = 0.724$, $F = 30.12$. The discriminant boundary value was found to be -0.015625 , higher (or equal) \hat{Z} values indicating barge shipments and lower values corresponding to rail shipments.

The microeconomic nature of this model's data requirements, as illustrated above, could cause data collection problems over and above those commonly encountered in econometrics research. Also, this technique does not provide the capability of analyzing the impact of new modes (e.g., energy by wire). Nevertheless, the power of the technique in exclusive mode choice situations cannot be refuted.

The Herendeen Model. The Herendeen model [64] was developed at The Pennsylvania State University as part of a comprehensive transportation planning methodology [34]. The model assumes that O-D tonnage flows for each commodity class are available from prior stages of the planning process, and predicts the percentage shipped by each mode as a set of functions (one for each mode and commodity) of various transportation service variables.

The functional estimators of the Herendeen model are log-linear regression equations, as follows:

$$P_k(X_{igh}) = a_{ok} R_k^{a_1} C_k^{a_2} T_k^{a_3} F_k^{a_4} \quad 6-8$$

with the constraint

$$\sum_k P_k(X_{igh}) = 100$$

where

$P_k(X_{igh})$ = percentage of X_{igh} shipped by mode k

X_{igh} = tons of commodity i shipped from node g to node h

R_k = reliability of mode k

C_k = relative cost of using mode k

T_k = relative transit time for mode k

F_k = relative service frequency provided by mode k

Relative values are all specified with respect to the "best" service provided by any mode between nodes g and h.

Herendeen reports in depth the difficulties encountered in obtaining simultaneous observations of the various data values needed to estimate the model's parameters. Consequently, the model has been tested only with

highly aggregated "national average" data and has never been applied at the intended scale.

Conclusions. The three models described above all use statistical methods for predicting freight modal split and, hence, suffer from the same problems of methodology and data availability as do the various structural forecasting techniques reviewed earlier. Nonetheless, both the Northwestern and Herendeen models appear to be viable approaches to the modal split problem and should be explored further as the requisite comprehensive data become available. The Silberberg modal is essentially a variant of Herendeen's procedure and is not considered further here due to its dependence upon development of a distribution model.

As with structural forecasting methods, implementation of a statistical modal split model is a long-term proposition, and some interim procedure is needed to make waterborne transport demand figures responsive to the level of service provided by the waterway. Such a procedure is the diversion curve method proposed below.³

2. A Diversion Curve Modal Split Model

Diversion curves have been used for quite some time in passenger transportation studies to allocate passenger flows among competing routes or modes on the basis of relative service levels. Conceptually, there is no reason why similar techniques should not be applicable to freight transportation. In particular, it appears that diversion curves could be used to estimate how much of the potential waterborne commerce between two ports would be shifted to other modes of transport as a function of tow delays.

³ More detailed descriptions of both the existing models reviewed in this section and the proposed diversion curve model may be found in a paper by Staadeker and Bronzini [65].

Figure 6-2 illustrates a proposed modal split diversion curve. The curve plots the percentage of potential waterborne commerce which would actually be shipped by water at various values of average tow delay, say, in units of hours per 100 miles. This curve is easily formulated as the following exponential function:

$$P(x) = a e^{-x^2/(2b^2)} \quad 6-9$$

where

$P(x)$ = percentage of potential waterborne O-D tonnage actually shipped by water

x = average tow delay between origin and destination, hr./100 mi.

a, b = curve parameters

Examination of this function and its derivatives reveals the following desirable properties:

$$P(0) = a = P_{\max}$$

$$\lim_{x \rightarrow \infty} P(x) = 0 = P_{\min}$$

$$P''(b) = 0$$

Hence, the parameter "a" is the zero-delay value of percentage-by-water, and parameter "b" is the delay value at which the curve's inflection point occurs. The corresponding $P(x)$ value is found to be:

$$P(b) = a e^{-b^2/(2b^2)} = a e^{-0.5} \cong 0.607a$$

Thus, "b" is the delay at which approximately 39% of the zero-delay traffic will be diverted to other modes.

The definitions of the curve parameters derived above provide a means of estimating these values on an intuitive or judgmental basis. A simple

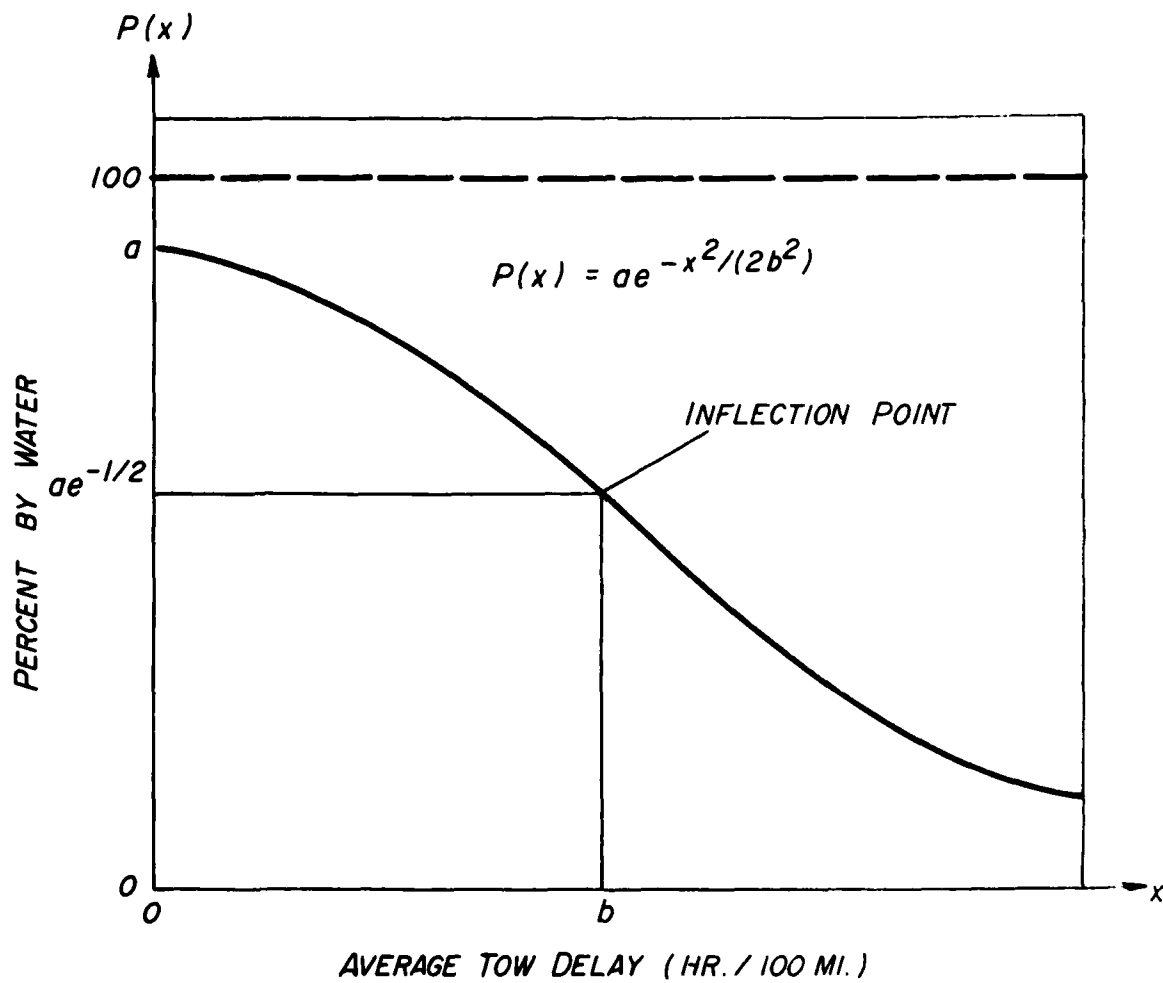


Figure 6-2 Modal Split Diversion Curve

statistical parameter estimation procedure is also available. Taking the natural logarithm of both sides of 6-9 produces:

$$\ln P(x) = \ln a - \frac{1}{2b^2} x^2 \quad 6-10$$

Since this equation is structurally identical to 6-1, simple linear regression can be used to estimate "a" and "b" given observations on (P(x), x).

It would appear initially that generation of consistent data values for parameter estimation purposes is an insurmountable obstacle. However, the demand forecasting and simulation models can be used to advantage here. Historical commodity flow records maintained by the Corps can be used to ascertain how much of each commodity actually moved on a waterway for a given point in time. Elements of the commodity flow forecasting method could then be applied to determine what the corresponding potential waterborne commerce was, given historical values for the exogenous variables entering into the flow forecasts. Finally, if consistent delay data for the same period of record are not available, the waterway system which existed at that time could be simulated, using the historical demand as input. The resulting average delay values output by the simulation model, together with the percentage-by-water values derived in the first two steps, constitute the required data set. Use of this method has the corollary advantage that the parameter estimates will be sensitive to the characteristics of the forecasting and simulation models, thus promoting the cohesiveness of the model system.

Application of the proposed model will require specification of the scale at which the model is to operate. As a minimum, it appears that one curve will be required for each commodity group. Different curves could also be generated for different reaches of a waterway, and the curves could

be stratified on the basis of trip length or some other variable. It should also be noted that the model structure is completely general, and some other independent variable could be used. Likely candidates here include delay difference, delay ratio, travel time difference or ratio, or some general impedance unit combining elements of travel time, rate, loss, and damage, etc.

Finally, the model is capable of generalization on several fronts. A natural extension is to consider the use of diversion surfaces, where one dimension might represent diversion to rail, another diversion to pipeline, and so on. The model also could be utilized within a more sophisticated demand forecasting framework. For example, a structural forecasting model could be used to forecast O-D commodity flows for all modes, and then the waterway's share of total demand determined with a statistical model sensitive primarily to rate and other nondelay service variables. This zero-delay waterway transport demand could serve as the potential demand estimate needed for the diversion curve modal split model. This idea is very similar to the two-stage modal split approach suggested in the Task Force report [36].

Summary and Conclusions

The waterway systems analysis methodology outlined in preceding section is intended to be a logical and orderly mechanism by which the Corps of Engineers can predict the equilibrium values of waterway transportation demand and level of service for any waterway system. These equilibrium values, in turn, will be prime inputs to a project selection procedure, regardless of what other consequences must also be included in the evaluation process. This is so because consideration of the nontransport effects of a waterway navigation project will normally involve some sort of a

trade-off analysis, and such analyses can be useful decision aids only if the direct economic impacts are reliably estimable.

This study focused almost entirely upon the demand analysis problem, primarily because techniques for dealing with it are much less developed than those for modeling transport supply phenomena. Progress toward implementation of an equilibrium model system for waterway planning will be minimal until viable demand models are forthcoming.

Two overriding themes became evident in the authors' review of commodity flow forecasting and modal split techniques. These are: (1) there are formidable obstacles to the development of econometric or statistical waterborne transport demand models; but (2) a great deal can be done with relatively simple methods to improve existing demand forecasting techniques, so as to make the resulting waterborne commerce predictions more objective and more sensitive to waterway service levels.

Related to the first of the above points is the fundamental issue of who should be performing transportation demand analyses on a nationwide basis. The authors have alluded several times to their conviction that all transportation planning in the United States, or at least all such planning of a regional scope, should be using the same basic demand data and forecasts. In fact, closer intermodal coordination of all aspects of planning would seem to be a desirable goal. The U.S. Department of Transportation is supposed to be fostering such cooperation, but there is little evidence of significant DOT efforts in this area. Preparation of national O-D commodity flow tables would be a valuable and necessary first step toward intermodal transportation planning, and the Corps should actively support an interagency effort in this direction.

In the interim (which could prove to be a fairly long period of time), the Corps should follow up the second point raised above. The first-level improvements in demand forecasting techniques advocated in this chapter should be instituted immediately. As experience is gained in the use of the model system of Figure 6-1, various improvements to the initial demand models can be experimented with. This evolutionary approach to the development of a waterway systems planning methodology will enable Corps personnel to increase gradually their proficiency in the use of systems models, while at the same time allowing the continuing stream of project studies to be processed without undue delay.

It must be emphasized that the time has come for the Corps either to reject the idea of waterway systems analysis or to implement a first generation model system. Further methodological surveys or state-of-the-art studies will be of little value. Only by squarely facing the problems of developing and implementing a waterway systems planning methodology can the Corps determine what course to pursue for future navigation studies.

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APPENDIX

PENN STATE PUBLICATIONS ON ANALYSIS OF WATERWAY SYSTEMS

This appendix lists publications by Penn State authors relating to Analysis of Waterway Systems, for the period 1965-1972.

PTTSC Publications

The reports listed in this section have all been published by the Pennsylvania Transportation and Traffic Safety Center, The Pennsylvania State University, University Park.

1. Research Reports

Waterway Systems Simulation:

- Vol. I Summary Report. J. L. Carroll and M. S. Bronzini. TTSC 7108, Aug. 1971, 126 pp.
- Vol. II WATSIM: A Waterway Transport Simulator. J. H. Gimbel III. TTSC 7109, Aug. 1971, 194 pp.
- Vol. III TOWGEN: A Tow Generation Model for Inland Waterway Simulation. M. S. Bronzini. TTSC 7110, Aug. 1971, 146 pp.
- Vol. IV LOKSIM: A Multiple Chamber Lock Simulation Model. J. C. Hayward. TTSC 7111, Aug. 1971, 91 pp.
- Vol. V Simulation of Multiple Channel Deep Draft Navigation Systems. J. C. Rea and D. C. Nowading. TTSC 7112. Aug. 1971, 212 pp.
- Vol. VI Application of System Simulation Models: Ohio River Navigation Study. J. H. Herendeen, Jr. and Paul J. Staadeker. TTSC 7113, Aug. 1971, 221 pp.

Simulation Analysis of a Multiple Chamber on the Inland Waterways. J. C. Hayward. TTSC 7211, Aug. 1972.

Analysis of Waterway Systems: Summary Report. J. L. Carroll, M. S. Bronzini and J. C. Hayward. TTSC 7212, Sept. 1972.

2. Technical Memoranda

Waterway Systems Simulation:

- No. 1 Working Papers. J. L. Carroll and M. S. Bronzini. Aug. 1971, 58 pp.
- No. 2 Calibration of TOWGEN and WATSIM. J. H. Herendeen, Jr. Aug. 1971, 33 pp.
- No. 3 Simulation Study of a Ten-Lock Subsystem for Illinois Waterway and Upper Mississippi River Navigation. J. L. Carroll and M. S. Bronzini. Sept. 1971, 182 pp.
- No. 4 Design and Stages of Development of an Automated Information System for Inland Waterway Evaluation and Planning. J. H. Gimbel III. Aug. 1971, 79 pp.
- No. 5 Preliminary Formulation of an Evaluation Model for Waterway Systems Planning. M. S. Bronzini. Aug. 1971, 59 pp.

Analysis of Waterway Systems:

- No. 6 Determination of Steady State Conditions for Waterway Simulation Experiments. K. J. Desai. Technical Note 68, June 1972, 36 pp.
- No. 7 Estimating the Variance of the Sample Mean of Autocorrelated Data in Simulation Experiments. S. Rao. Technical Note 74, July 1972, 22 pp.
- No. 8 A Study of Tow Arrival Processes at Inland Waterway Locks. K. J. Desai. Technical Note 76, Sept. 1972, 13 pp.
- No. 9 A Simulation Study of Methods for Increasing Capacity Utilization on the Inland Waterways. S. Rao and M. S. Bronzini. Technical Note 71, Aug. 1972, 74 pp.
- No. 10 The Development of a Barge Tow Speed Function Using Regression Analysis. J. W. Hummel. Technical Note 77, Sept. 1972, 46 pp.
- No. 11 Forecasting Commodity Flows on the Inland Waterways. J. E. McLauchlan. Technical Note 69, Aug. 1972, 36 pp.
- No. 12 Transport Flow Statistics. J. E. McLauchlan. Technical Note 70, Aug. 1972, 28 pp.
- No. 13 A Review of Techniques for Predicting Freight Modal Split. P. J. Staadeker and M. S. Bronzini. Technical Note 72, Aug. 1972, 22 pp.

3. Other PTTSC Publications

The Lake Erie-Ohio River Canal and Pennsylvania's Future Transport Requirements. J. L. Carroll. TTSC 6903, 1969, 61 pp.

Systems Analysis of Waterway Improvements: Status and Prospectus. J. L. Carroll and M. S. Bronzini. TTSC 7004, 1970, 7 pp.

Status Report: Illinois-Mississippi Waterway Analysis--A Systems Approach. J. H. Gimbel III. Technical Note 14, Sept. 1970, 44 pp.

The Application of Time-Lapse Photography to Locking Operations Studies. T. J. Waytena. Technical Note 16, Nov. 1970, 9 pp.

Simulation Studies of the Proposed Lake Erie--Ohio River Canal. J. W. Hummel. Technical Note 46, Feb. 1972, 68 pp.

A Simulation Model for the Study of Two-Way Ship Traffic Through Canals Which Offer Multiple Routing Options. J. C. Rea and D. C. Nowading. Technical Note 55, Apr. 1972, 22 pp.

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